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MILITARY HANDBOOK

ELECTROMAGNETIC (RADIATED) ENVIRONMENT CONSIDERATIONS FOR DESIGN AND PROCUREMENT OF ELECTRICAL AND ELECTRONIC EQUIPMENT, SUBSYSTEMS AND SYSTEMS

PART-1B

GENERAL GUIDANCE

AMSC N/A

AREA EMCS

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DEPARTMENT OF DEFENSE
WASHINGTON D.C. 20360

ELECTROMAGNETIC (RADIATED) ENVIRONMENT CONSIDERATIONS FOR DESIGN AND PROCUREMENT OF ELECTRICAL AND ELECTRONIC EQUIPMENT, SUBSYSTEMS AND SYSTEMS

MIL-HDBK-235-1B

1. This Military Handbook is approved for use by all Departments and Agencies of the Department of Defense.

2. Every effort has been made to reflect the latest information on the electromagnetic environment. It is the intent to review this handbook periodically to insure its completeness and currency. However, several factors dictate that the document be revised periodically. The factors include advances in emitter state-of-the-art, increased knowledge of hostile emitter characteristics or revised definitions of emitter and missile deployments. The document can be updated on a bi-annual basis.

3. Procedures for the release of Part 2, 3, 4, and 5 of MIL-HDBK-235 to Industry. Other parts of MIL-HDBK-235 may be released to private industry, when necessary, for the performance of a Department of Defense contract, or to bidders, if required for the preparation of response to an invitation-for-bid, in accordance with the following procedures:

a. Releasing Service or Command. The following activities are authorized to release other parts of this handbook.

- For Air Force contracts and bids - ASD/ENES
- For Army contracts and bids - U.S. Army Communication Research and Development Command
- For Navy and other DoD agencies contracts and bids - Space and Naval Warfare Systems Command

Prior to releasing other parts of the handbook, the above activities shall:

(1) Ensure that the conditions of paragraph 7-106d of DoD Dir 5200.1-R (Information Security Program Regulation) are met.

(2) Critically review existing and proposed contract requirements to ensure that all data being requested are actually required (based on system or platform type, function, intended installation and expected electromagnetic environment). When all data are not required, the handbook shall be tailored by the releasing command or service so that only applicable portions of the classified parts of the handbook are sent to bidders or contractors. Reference to the levels in Part 1, TABLE II,

may be adequate for bid purposes.

(3) Keep a record of all releases to contractors and bidders.

b. Contracting officers and security managers. Co[illegible]racting Officers and Security Managers will ensure tha the following requirements are specifically included in the contract itself, invitation-for-bid or in the Contract Security Classification Specification (DD Form 254);

(1) The material does not become the property of the bidder or contractor and may be withdrawn at any time. Upon close of bid or expiration of the contract, Classified parts of MIL-HDBK-235, and any material using data from the handbook shall be returned to the contracting officer or authorized representative for final disposition.

(2) Bidders and Contractors shall not release classified parts of MIL-HDBK-235 to any activity or person of the contractor's organization not directly engaged in providing services under the contract or to another contractor (including subcontractors), government agency, private individual, or organization.

(3) Classified parts of MIL-HDBK-235 shall not be released to foreign nationals or immigrant aliens who may be employed by the contractor, regardless of their security clearance level.

(4) Classified parts of MIL-HDBK-235, shall not be reproduced.

(5) The bidder and contractor shall maintain such records as will permit them to furnish, on demand, the names of individuals who have access to foreign intelligence material in their custody.

4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to:

COMMANDER
SPAWAR 2243
SPACE AND NAVAL WARFARE SYSTEMS COMMAND
2451 CRYSTAL PARK 5
WASHINGTON D.C. 20363-5200

by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FOREWORD

Department of Defense activities have experienced increasingly serious problems of damage and performance degradation to electrical and electronic equipments, subsystems and systems due to inadequate consideration of the intended operational electromagnetic environment in their initial design. To correct this, general design requirements and limits in existing electromagnetic compatibility (EMC) and interference (EMI) standards must be analyzed to determine their suitability and applicability for a given development and procurement. The standards are to be tailored by the Procuring Activity to the peculiarities of the specific equipment, its mission and operational concepts, the probabilities of achieving intra- and intersystem EMC, program cost objectives and the anticipated operational electromagnetic environment. Definitive postulations of the total intended environment are required at various stages during the system design, as well as requirements to demonstrate operation and survivability in those environments. An initial postulation of the environment should be included in the specification. This postulation may be based on the assumption that the emitters with the largest radiated levels represent the greatest threat. From this, the extreme electromagnetic environment parameters which can be encountered during the system's life cycle may be documented. Subsequent analyses may show that the initial assumptions yielded extremely high environment levels thus necessitating revisions of the initially postulated environment. The revised environment levels could then be used by the designer or testing organization.

This document provides information and guidance to the project manager, acquisition manager and others responsible for the design, test and procurement of electrical and electronic components, equipments, subsystems and systems on the representative maximum electromagnetic environment which may be encountered at various stages of their life cycle. The intent of this document is not to provide detailed electromagnetic environment specifications since each equipment and procurement is somewhat unique, but rather, to provide guidance and information which must be weighed during design and procurement. Use of this document will require engineering judgment. Therefore, it is advisable to search out the additional electromagnetic environment data in the referenced publications when more precise or detailed environmental information is required.

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SECTION 1: INTRODUCTION

1 1 Scope. The intent of this handbook is to provide and establish a uniform approach for the protection of military electronics from the adverse effects of the electromagnetic environment. The handbook is applicable to any electrical and electronic equipment, subsystem or system which may be exposed to an electromagnetic environment during its life cycle, including the following:

a. Aerospace and weapons systems and associated subsystems and equipments.
b. Ordnance.
c. Support and checkout equipment and instruments for (a) and (b) above.

1.2 Purpose. This handbook provides:

a. Information on the electromagnetic environment for consideration in the design and procurement of new systems, subsystems and equipments which may be exposed to electromagnetic radiation environment levels during their life cycle.

b. Information for use in tailoring the radiated susceptibility requirement RS03 of MIL-STD-461 and the requirements of MIL-E-6051, and to supplement the requirements of MIL-STD-1385 and MIL-STD-1512 to ensure adequate consideration of the electromagnetic environment during equipment and system design.

1.3 Use. The information contained herein will be valuable in implementing the military departments' policies on tailoring of requirements. Tailoring of susceptibility requirements must not violate International agreements. In the event that there are essential reasons for non-conformance with such an agreement, the signatory Nations must be consulted, as required by the agreement. Care should be taken to ensure that tailoring does not restrict an equipment for use in only one system or installation; therefore susceptibility levels less stringent than the applicable levels in MIL-STD-461 should not be used. Contractors shall not use this handbook as justification for changing any contractual provision based on MIL-STD-461 or MIL-E-6051 or any EMC or EMI control or test plan, as may be required by the contract.

1.4 Format. This handbook is issued in five parts. Part 1 gives general information and approximate electromagnetic environment levels; Parts 2 and 3 describe the electromagnetic levels which may be encountered from friendly and hostile emitters, respectively, as well as emitter characteristics; Part 4 describes the electromagnetic environment levels which may be encountered in specific Army installations; and Part 5 describes the predicted typical electromagnetic environment levels which may be encountered by platforms operating in four US Naval Battle Force scenarios. Table I is an index of the tables in other parts of this handbook.

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TABLE I Index of Representative Electromagnetic Environment Levels and Emitter Characteristics. (Continued)

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SECTION 2: REFERENCED DOCUMENTS

2.1 The following documents of the issue in effect on date of invitation for bids, request for proposal, form a part of this handbook to the extent specified herein.

SPECIFICATIONS

MILITARY

MIL-E-6051	- Electromagnetic Compatibility Requirements, Systems.

STANDARDS

MILITARY

MIL-STD-461	- Electromagnetic Interference Characteristics, Requirements for Equipments.
MIL-STD-1385	- Preclusion of Ordnance Hazards in Electromagnetic Fields, General Requirements for
MIL-STD-1512	- Electroexplosive Subsystems, Electrically Initiated, Design Requirements and Test Methods

HANDBOOKS

MILITARY

MIL-HDBK-235 Part 2	- Electromagnetic Radiation Environment fromFriendly or Own Force Emitters.
MIL-HDBK-235 Part 3	- Electromagnetic Radiation Environment from Hostile Force Emitters
MIL-HDBK-235 Part 4	- Electromagnetic Radiation Environment, Army Installations
MIL-HDBK-235 Part 5	- Predicted Electromagnetic Environments forFour Selected Battle Force Scenarios
MIL-HDBK-237	- Electromagnetic Compatibility/ Interference Program Requirements
MIL-HDBK-253	- Guidance for the Design and Test of Systems Protected against the Effects of Electromagnetic Energy

AIR FORCE

AFSC DH1-4	-	Air Force Systems Command Design Handbook, Electromagnetic Compatibility
AFSC DH2-7	-	Air Force Systems Command Design Handbook, "System Survivability"

(Copies of specifications, standards, handbooks, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Non-Government Publications. The following document forms a part of this document to the extent specified herein. Unless otherwise specified, the issues of the document which are DOD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are the issues of the document cited in the solicitation.

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

ANSI C63.14	-	Standard dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatic Discharge (ESD).

(Applications for copies should be addressed to the IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331.)

SECTION 3: DEFINITIONS

3. Definitions. The terms used in this handbook are defined in ANSI C63.14.

SECTION 4: DEFINING REQUIREMENTS

4.1 General. One of the basic objectives of the Department of Defense is to provide equipments and systems whose performance will not be adversely affected by the electromagnetic environment during all phases of the equipment or system life cycle. The effects may be either permanent, in which case the system will not operate until the damage has been repaired, or temporary, in which case the system will operate when the emissions causing the degradation are reduced or removed. Different effects can be produced, depending on the victim. Examples are:

a. Burnout or voltage breakdown of components, antennas, and so forth.
b. Performance degradation of receiver signal processing circuits.
c. Erroneous or inadvertent operation of electromechanical equipments, electronic circuits, components, ordnance, and so forth.
d. Unintentional detonation or ignition of electro-explosive devices, Flammable materials, and so forth.
e. Personnel injuries.

The effects on a given victim in a specific electromagnetic environment depend on the victim susceptibility characteristics, amplitude, frequency and time-characteristics of the environment, response time and frequency response of victim, and so forth. To prevent these problems, it is imperative that the possible effects of the electromagnetic environment on each new system be considered by the designer. A requirement to demonstrate satisfactory performance in a defined environment should be included in the equipment, subsystem or system (see 4.4) specification. MIL-HDBK-253 provides guidelines on the use of the electromagnetic environment data contained in this handbook as well as general information on the design and test of equipment, systems and platforms.

4.2 Developing the performance requirement. In developing the performance requirement for equipments, subsystems, and systems that may be exposed to the electromagnetic environment, various aspects should be considered as described in 4.2.1 through 4.2.5.

4.2.1 Environment profile. Each equipment, subsystem and system will be exposed to several different electromagnetic environments during its life cycle. The tables in the other parts of this handbook are intended for use in defining representative environment levels (see 4.3) to which each may be exposed. It is necessary to define each distinct environment. For example, a missile will be exposed to different environments during shipment, storage, checkout, launch, and during approach to a target.

4.2.2 Configuration. The configuration of each equipment, subsystem and system will vary depending on its location with the result that its susceptibility to the electromagnetic environment may also vary. Therefore, in developing the performance requirement the modes of operation, shielding, and so forth, in each of the environments defined should be identified.

4.2.3 Operate vs. survive. It is important to distinguish between the conditions of operate and survive. There is usually a significant difference between the environment levels that will degrade performance and the levels that will permanently damage. In addition, there are many precautions that can be taken to protect an equipment from damage when it is not operating that are not feasible when it is operating.

4.2.4 Susceptibility. The susceptibility characteristics of the equipment, subsystem or system may be different depending on the design characteristics. The equipment may be frequency selective or may respond to a broad frequency range. Certain victims have response times in milliseconds and are affected by short-term, peak levels in the environment, whereas others are affected by heating and may respond slowly to average signal levels. All of these characteristics as well as the shielding integrity, choice of components and use of filtering must be considered when evaluating the effect of the electromagnetic environment on the equipment, subsystem or system. Furthermore, non-metallic materials are being considered for use on new platforms. Since these non-metallics provide little or no shielding, the installed system, subsystem or equipment can be exposed to environmental levels much higher than would be encountered on a platform with conventional metallic materials.

4.2.5 Future considerations. The definition of the electromagnetic environment which an equipment, subsystem or system may encounter should also include consideration of any possible future applications of the equipment, subsystem, or system and changes in the environment. Equipments designed to operate in one environment may be installed in another, or used to perform functions and missions that were not planned when the equipments were originally designed. Therefore, it is important to realize that although the cost of an equipment, subsystem, or system may increase when a severe electromagnetic environment is predicted, the increase may be justified in terms of adaptability for future applications.

4.3 Environment levels. The electromagnetic environment levels provided in Parts 2, 3, 4, and 5 are based on actual measurements, or predictions where measurements were not feasible. They are representative maximum values for each of the frequency bands. Approximate levels are given in TABLE II of this handbook for general information. However, care should be exercised if these values are to be used for anything other than general information.

4.3.1 Modification of environmental levels. The electromagnetic environmental levels are given in terms of peak and average power density and field strength. However, there are many other parameters which could influence the effect of the environment on a system, including:

Antenna scan rates	Pulse width
Antenna patterns	Pulse repetition frequency
Antenna polarization	Pulse rise and decay time
Antenna aperture	Spectrum coverage

Relative location and proximity to other emitters, both friendly and hostile.

All known information concerning the environment within which an equipment, subsystem, or system must operate should be considered when evaluating its operation in its intended electromagnetic environment During development it is advisable to search out additional environmental data to ensure successful operation of the completed system, subsystem or equipment. Additional information concerning the sources of the environment levels in this document can be obtained from the preparing activity or the departmental custodians, as appropriate.

4.3.2 Conditions precluding exposure. When defining the electromagnetic environment within which an equipment, subsystem or system will be required to survive and operate during its life cycle, any operational or installation conditions that can preclude exposure to these levels and any additional information concerning the environment that may affect the impact of these levels should be considered. For example, the complement of intentional emitters on a platform or site will provide an indication of those frequency bands where high environment levels can probably be encountered. Furthermore, dimensional restrictions and intervening structures may exist thereby causing a system, subsystem or equipment to operate in the near or induction field region of an antenna. Other factors which must be considered are given below:

a. Limited platform usage. Many electronic equipments, subsystems, and systems are procured for installation on specified hulls, aircraft, ship types or land facilities. Definition of the electromagnetic environment to which the equipments and systems may be exposed should include consideration of the actual radiation levels based on the actual emitters installed or planned for installation on the specific site or platform rather than the general radiation levels.

b. Known location. Many electronic systems, subsystems, and equipments will be permanently installed at known locations. Definition of the electromagnetic environment to which they may be exposed should include consideration of the possibility that exposure to certain of the general radiation levels is unlikely because of the location of the new system, subsystem, or equipment relative to the sources of the radiation levels.

c. Operational usage. There are certain electronic systems which, because of their functions, may not be exposed to the general radiation levels. For example, backup equipment may not be exposed to radiation from primary equipment, and systems used when entering port normally will not be exposed to radiation from the fire control radars. Definition of the electromagnetic environment to which the systems may be exposed should include consideration of operational procedures which may preclude exposure to some of the environmental levels.

TABLE II. Approximate EM Environment Levels.

LOCATION	FREQ. RANGE (MHz)	APPROXIMATE NEAR FIELD EM LEVELS			
		Pwr Dens (mW/cm^2)		Fld Stgth (V/m)	
		Peak	Avg	Peak	Avg
MIL-HDBK-235 Part 2 (Partial)					
Table I - Factory-to-Depot	< 35 35-2000 > 2000	- - -	- - -	- - -	10 5 20
Table II - Depot-to-Checkout	< 35 35-2000 > 2000	- - -	- - -	- - -	10 5 20
Table III - Checkout Areas Aboard Ship	< 30 30-2000 > 2000	- - -	- - -	1 32 1	1 1 1
Table IV - Hangar Deck (CV's and CVN's)	< 30 30-2000 > 2000	- - -	- - -	32 250 234	10 55 10
Table V(a) - Flight Deck of Aircraft Carriers (CV's and CVN's)	< 30 30-2000 > 2000	- - -	- - -	200 5,100 9,700	100 183 183
Table V(b) - Weather Decks, Missile Launching Ships (CG, CGN, DDG, FFG & FF's)	< 30 30-2000 > 2000	- - -	- - -	200 5,100 9,700	100 183 183
Table V(c) - Weather Decks, Non-Missile Combat Ships	> 30 30-2000 < 2000	- - -	- - -	200 5,100 7,220	100 183 183
Table VI(a) - Landbased Installations (Inside Xmtr Bldg and Outside all other structures)	< 30 30-2000 > 2000	- - -	- - -	20 40 1,500	10 5 40
Table VI(b) - Landbased Installations (Inside all other structures)	> 30 30-2000 > 2000	- - -	- - -	10 40 40	1 1 1
Table VII - Envelope of Maximum EM Environment Levels in Main Beam of US Shipboard Emitters	< 30 30-2000 > 2000	1 5,000 205,000	1 60 3,100	55 4,250 31,000	55 460 3,500
Table VIII - Envelope of Maximum EM Environment &2 Levels in Main Beam of US Airborne Emitters	< 30 30-2000 > 2000	10 5,500 45,000	10 25 800	185 4,500 31,000	185 285 1,750
Table IX - Envelope of Maximum EM Environment Levels in Main Beam of US Landbased Emitters	< 30 30-2000 > 2000	0.3 55,000 210,000	0.3 250 450	30 15,000 28,000	30 950 1,300

TABLE II. Approximate EM Environment Levels. (Continued)

LOCATION	FREQ. RANGE (MHz)	APPROXIMATE NEAR FIELD EM LEVELS			
		Pwr Dens (mW/cm^2)		Fld Stgth (V/m)	
		Peak	Avg	Peak	Avg
MIL-HDBK-235 Part 3 (Partial)					
Table I - Maximum EM Environmental Levels for Hostile Shipboard Emitters	< 30 30-2000 > 2000	0.4 14,500 250,000	0.4 90 450	40 7,300 30,000	40 600 1,400
Table II - Maximum EM Environment Levels for Hostile Airborne Emitters	< 30 30-2000 > 2000	- 2,510 50,000	- 4 65	- 3,100 14,000	- 125 500
Table III - Maximum EM Environment Levels for Hostile Landbased Emitters	< 30 30-2000 > 2000	4 700,000 800,000	4 7,000 275,000	120 55,000 850,000	120 5,500 33,000
Table X - Actual Hostile Jammers	< 2000 > 2000	25 35	2 30	300 360	85 320
Table XI - Postulated Hostile Jammers	< 2000 > 2000	4,500 35,000	25 350	4,100 12,000	300 1,200
MIL-HDBK-235 Part 4 (Army only)					
Table I - Land Environment (Pulsed & Non-Pulsed Transmitters)	< 50 50-1000 > 1000	- - -	- - -	- - -	300 800 800
Table II - Land Environment (Pulsed Transmitters)	> 50 50-1000 > 1000	- - -	- - -	10 20,000 25,000	- - -

4.4 Evaluation guidance. A requirement to demonstrate satisfactory operation in the defined environment should be included in the specific equipment, subsystem or system specification. Compliance with MIL-E-6051, MIL-STD-461 or MIL-STD-1385 would provide for a testing requirement, but only to lower levels of electromagnetic radiation. The electromagnetic environment levels in this handbook are substantially higher than those in MIL-E-6051, MIL-STD-461 and MIL-STD-1385; however, it should be noted that they are more difficult to generate and require careful consideration of the availability of test equipment and the type of testing laboratory, that is, military or civilian. Numerous alternatives are available for performing the evaluation, including the following:

a. Laboratory simulation. Prior to finalization of the design specification, a model of the platform, system, subsystem or equipment being procured may be developed and its performance evaluated in a model of the anticipated operational electromagnetic environment. The environment model should include all anticipated friendly and hostile, intentional and unintentional electromagnetic emissions. The objective of this effort is to validate the proposed design parameters and make necessary modifications prior to hardware development. The models can then be updated and re-used throughout the life cycle of the platform, system, subsystem or equipment to evaluate proposed hardware design changes and engineering change proposals (ECP's) as well as to reduce the need for costly field testing.

b. Anechoic chamber simulation. The performance of the Advanced Development and Engineering Development Models may be evaluated by a series of tests in an anechoic chamber wherein the anticipated electromagnetic environment developed as in (a) above is scaled down and simulated by limiting the electromagnetic environment levels, frequency ranges and test sample shielding.

c. Full-Scale field testing. The performance of this type of test may necessitate use of a military test facility in lieu of contractor's due to the difficulty in generating the high level electromagnetic environment levels. Such tests are usually quite costly since they may require installation of the system, subsystem or equipment on the intended platform. It is noted that data obtained from (a) and (b) above may reduce the requirement for field performance data.

4 5 Documentation. Provisions should be included in the procurement documentation to verify that the environment is considered throughout the contract. This can be accomplished by requiring the contractor to provide documentation similar to or an expansion of that described in MIL-STD-461 or MIL-E-6051 as indicated in 4.5.1 through 4.5.3.

4.5.1 Control plan. The techniques and procedures that will be used to enhance compliance with the performance requirements in the specified

electromagnetic environment should be described. This may be accomplished by requiring the contractor to expand the contents of the control plans which may be required by the contract, such as those described in MIL-E-6051 or MIL-STD-461.

4.5.2 Test plan. The test methods and equipment that will be used to demonstrate compliance with the performance requirements in the specified electromagnetic environment should be described. This may be accomplished by requiring the contractor or testing activity to expand the contents of the test plans which may be required by the contract, such as those described in MIL-STD-461 or MIL-E-6051.

4.5.3 Test report. The results performed to demonstrate compliance with the performance requirements in the specified electromagnetic environment should be documented and reviewed by the procuring activity. This may be accomplished by requiring the contractor or test activity to expand the contents of the test reports which may be required by the contract, such as those in MIL-STD-461 or MIL-E-6051.

Custodians:

Army - CR
Air Force - 11
Navy - EC

Preparing Activity:

Navy - EC
(Project EMCS-N128)

Review Activities:
Army - ER, AV, MI, AR
Navy - SH, AS, MC
Air Force - 10, 15, 17, 18, 19

User Activities:
Army - TE

METRIC
MIL-HDBK-423
15 May 93

MILITARY HANDBOOK

HIGH-ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION FOR FIXED AND TRANSPORTABLE GROUND-BASED C^4I FACILITIES

VOLUME I
FIXED FACILITIES

(METRIC)

AMSC N/A

FSC SLHC

<u>DISTRIBUTION STATEMENT X.</u> Distribution authorized to U.S. Government agencies and private individuals or enterprises eligible to obtain export-controlled technical data in accordance with DoD Directive 5230.25, 22 March 1991. Controlling DoD office is AFC4A/TNAB, 607 Pierce Street, Room 300, Scott AFB, IL 62225-5421.

FOREWARD

1. This military handbook is approved for use by all Departments and Agencies of the Department of Defense.

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: AFC4A/TNAB, 607 Pierce Street, Room 300, Scott AFB, IL 62225-5421, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

3. This document provides design guidance and examples of good practice to support the implementation of high-altitude electromagnetic pulse (HEMP) hardening and testing requirements of MIL-STD-188-125. It also includes management guidance for HEMP protection acquisition programs and hardness maintenance and hardness surveillance for operational facilities.

4. The handbook reflects the 26 June 1990 issue of MIL-STD-188-125.

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1. SCOPE

1.1 Purpose. The two-volume MIL-HDBK-423 handbook set provides information to managers and engineers responsible for the design, construction, testing, and hardness maintenance/hardness surveillance of fixed and transportable ground-based facilities that must be hardened against the high-altitude electromagnetic pulse (HEMP). The primary purpose of this Volume I is to provide detailed guidance to implement HEMP protection of fixed facilities in accordance with the requirements of MIL-STD-188-125, "High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C^4I Facilities Performing Critical, Time-Urgent Missions." Volume II provides similar guidance for ground-mobile and transportable facilities.

1.2 Content. This handbook provides design guidance and examples of good practice to support compliance with the requirements stated in MIL-STD-188-125. That standard calls for the establishment of an electromagnetic barrier to limit the magnitude of HEMP-induced electrical stresses that might reach mission-critical systems and components. The standard also establishes requirements and procedures for tests and inspections during construction, for acceptance testing of the HEMP barrier, and for functional hardness verification testing of the completed and operational facility. The handbook contains supporting information that offers guidance for fulfilling these requirements.

1.3 Applications. This volume of the handbook will support the design, construction, testing, hardness maintenance, and hardness surveillance of HEMP protection for fixed ground-based facilities in a HEMP-hardened command, control, communications, computer, and intelligence (C^4I) information-systems network. Such facilities include sensor systems, command and control processing centers, communications stations, and relay facilities.

1.4 Objectives. Nuclear survivability is essential to a credible military deterrent. This volume of the handbook explains and provides information for a standardized, low-risk HEMP hardening approach for fixed ground-based C^4I facilities. DoD-STD-2169 is referenced in MIL-STD-188-125 and in this handbook as the descriptive source for the HEMP environment. In all cases in this handbook, the HEMP environment and HEMP stresses are those defined in DoD-STD-2169.

2. APPLICABLE DOCUMENTS

2.1 Government documents.

2.1.1 **Specifications, standards, and handbooks.** The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the effective issue of the Department of Defense Index of Specifications and Standards (DoDISS) and supplement thereto.

SPECIFICATIONS

FEDERAL

FF-W-84	-	Washers, Lock (Spring).
FF-S-325	-	Shield, Expansion; Nail Expansion; and Nail, Drive Screw (Devices, Anchoring, Masonry).
FF-B-588	-	Bolt, Toggle: and Expansion Sleeve, Screw.

MILITARY

MIL-B-5087	-	Bonding, Electrical, and Lightning Protection, for Aerospace Systems.
MIL-Q-9858	-	Quality Program Requirements.
MIL-T-10727	-	Tin Plating: Electrodeposited or Hot-Dipped, for Ferrous and Nonferrous Metals.
MIL-F-15733	-	Filters and Capacitors, Radio Frequency Interference, General Specification for.
MIL-P-26915	-	Primer Coating, Zinc Dust Pigmented, for Steel Surfaces.
MIL-H-46855	-	Human Engineering Requirements for Military Systems, Equipment and Facilities.

STANDARDS

FEDERAL

FED-STD-368	-	Quality Control System Requirements.
FED-STD-1037	-	Glossary of Telecommunication Terms.

MILITARY

MIL-STD-22	-	Welded Joint Design.
MIL-STD-100	-	Engineering Drawing Practices.
MIL-STD-130	-	Identification Marking of U.S. Military Property.
MIL-STD-188-124	-	Grounding, Bonding, and Shielding for Common Long Haul/Tactical Communication Systems, Including Ground-Based Communications-Electronics Facilities and Equipments.
MIL-STD-188-125	-	High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C^4I Facilities Performing Critical, Time-Urgent Missions.
MIL-STD-202	-	Test Methods for Electronic and Electrical Component Parts.
MIL-STD-220	-	Method of Insertion-Loss Measurement.
MIL-STD-248	-	Welding and Brazing Procedure and Performance Qualification.
MIL-STD-461	-	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference.
MIL-STD-470	-	Maintainability Program for Systems and Equipment.
MIL-STD-471	-	Maintainability Verification/Demonstration/ Evaluation.
MIL-STD-721	-	Definition of Terms for Reliability and Maintainability.
MIL-STD-756	-	Reliability Modeling and Prediction.
MIL-STD-781	-	Reliability Testing for Engineering Development, Qualification, and Production.
MIL-STD-785	-	Reliability Program for Systems and Equipment Development and Production.
MIL-STD-882	-	System Safety Program Requirements.
MIL-STD-973	-	Configuration Management.
MIL-STD-1261	-	Arc Welding Procedures for Constructional Steels.
MIL-STD-1472	-	Human Engineering Design Criteria for Military Systems, Equipment, and Facilities.
MIL-STD-1516	-	Unified Code for Coatings and Finishes for DoD Materiel.
MIL-STD-1568	-	Materials and Processes for Corrosion Prevention and Control in Aerospace Weapons Systems.

MIL-STD-1892	-	Welding, Arc and Oxyfuel Gas, Process and Requirements for.
MIL-STD-2165	-	Testability Program for Electronic Systems and Equipments.
DoD-STD-2169	-	High-Altitude Electromagnetic Pulse (HEMP) Environment (U) (document is classified Secret).
MIL-STD-2219	-	Fusion Welding for Aerospace Applications.

HANDBOOKS

MILITARY

MIL-HDBK-217	-	Reliability Prediction of Electronic Equipment.
MIL-HDBK-232	-	Red/Black Engineering: Installation Guidelines.
MIL-HDBK-411	-	Power and the Environment for Sensitive DoD Electronic Equipment.
MIL-HDBK-419	-	Grounding, Bonding, and Shielding for Electronic Equipment and Facilities.
MIL-HDBK-472	-	Maintainability Prediction.
MIL-HDBK-729	-	Corrosion and Corrosion Prevention Metals.
DoD-HDBK-763	-	Human Engineering Procedures Guide.
DoD-HDBK-791	-	Maintainability Design Techniques.
MIL-HDBK-1004/10	-	Electrical Engineering Cathodic Protection.

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Naval Publications and Forms Center (ATTN: NPODS), 5801 Tabor Avenue, Philadelphia, PA 19120-5099.)

2.1.2 **Other Government documents, drawings, and publications.** The following other Government documents, drawings, and publications form a part of this document to the extent specified herein. Unless otherwise specified, the issues are those currently effective.

DoD Manual 4270.1-M	-	Policy Guidelines for Installation Planning, Design, Construction and Upkeep.
DoD Directive 4270.5	-	Military Construction Responsibilities.
DoD Directive 5000.1	-	Defense Acquisition.
DoD Instruction 5000.2	-	Defense Acquisition Management Policies and Procedures.

DoD Directive 7045.7	-	Implementation of the Planning, Programming, and Budgeting System (PPBS).
DoD Directive 7045.14	-	The Planning, Programming, and Budgeting System (PPBS).
DNA-H-86-60	-	DNA EMP Engineering Handbook for Ground Based Facilities.
DNA-TR-89-281	-	Military Handbook for Hardness Assurance, Maintenance, and Surveillance (HAMS) Planning.
DNA-H-90-30	-	Program Management Handbook on Nuclear Survivability.
DNA-TR-91-87	-	High-Altitude Electromagnetic Pulse (HEMP) Hardness Maintenance/Hardness Surveillance Manual for HEMP Shielding Protection.
DNA-EMP-1	-	Electromagnetic Pulse (EMP) Security Classification Guide (U) (document is classified Secret).
MIL-BUL-36	-	U.S. Building Codes and Standards; an Overview.

(c opies of specifications, standards, handbooks, drawings, and publications required by contractors in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the Contracting Officer.)

2.2 **Non-Government publications.** The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the effective issue of the DoDISS. Unless otherwise specified, the issues of documents not listed in the DoDISS are those currently effective.

AMERICAN INSTITUTE OF STEEL CONSTRUCTION (AISC)

AISC S326 – Specification for the Design, Fabrication & Erection of Structural Steel for Buildings.

(Applications for copies should be addressed to the American Institute of Steel Construction, I.E. Wacker Drive, Suite 3100, Chicago, IL 60601-2001.)

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

ANSI/NFPA 70	-	National Electrical Code.
ANSI/NFPA 77	-	Recommended Practice on Static Electricity.
ANSI/NFPA 78	-	Lightning Protection Code.
ANSI/NFPA 101	-	Code for Safety to Life from Fire in Buildings and Structures.
ANSI/IEEE 142	-	Recommended Practice for Grounding of Industrial and Commercial Power Systems.
ANSI/NEMA 250	-	Enclosures for Electrical Equipment.
ANSI/IEEE 519	-	Guide for Harmonic Control and Reactive Compensation of Static Power Converters.
ANSI/UL 1283	-	UL Standard for Safety; Electromagnetic Interference Filters.
ANSI/AWS A2.4	-	Standard Symbols for Welding, Brazing, and Nondestructive Examination.
ANSI/AWS A3.O	-	Standard Welding Terms and Definitions Including Terms for Brazing, Soldering, Thermal Spraying, and Thermal Cutting.
ANSI/AWS A5.18	-	Carbon Steel Filler Metals for Gas Shielded Arc Welding, Specification for.
ANSI/IEEE C2	-	National Electrical Safety Code.
ANSI/IEEE C62.32	-	Standard Test Specifications for Low Voltage Air Gap Surge-Protective Devices (Excluding Valve and Expulsion Devices).
ANSI/IEEE C62.33	-	Standard Test Specifications for Varistor Surge-Protective Devices.
ANSI/IEEE C62.42	-	Guide for the Application of Gas Tube Arrester Low-Voltage Surge-Protective Devices.
ANSI/IEEE C62.45	-	Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits.
ANSI C84.1	-	Electrical Power Systems and Equipment – Voltage Ratings (60 Hz).
ANSI/AWS D1.1	-	Structural Welding Code - Steel.
ANSI/AWS D1.3	-	Structural Welding Code – Sheet Steel.
ANSI/AWS D9.1	-	Sheet Metal Welding Code.
ANSI/AWS Z49.1	-	Safety in Welding and Cutting.

(Applications for copies should be addressed to the American National Standards Institute, 11 West 42nd Street, New York, NY 10036.)

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM A6/A6M - Standard Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use.

ASTM A36/A36M - Standard Specification for Structural Steel.

(Applications for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187.)

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

C62.31 - Test Specifications for Gas-Tube Surge-Protective Devices.

C62.35 - Standard Test Specifications for Avalanche Junction Semiconductor Surge-Protective Devices.

(Applications for copies should be addressed to the Institute for Electrical and Electronics Engineers, 445 Hoes Lane, Post Office Box 1331, Piscataway, NJ 08855-1331.)

UNDERWRITERS LABORATORY (UL), INC.

UL 1449 - UL Standard for Safety; Transient Voltage Surge Suppressors.

(Applications for copies should be addressed to Underwriters Laboratory, Inc., 333 Phingsten Road, Northbrook, IL 60062.)

2.3 **Order of Precedence.** In the event of a conflict between the text of this document and MIL-STD-188-125, the text of MIL-STD-188-125 takes precedence.

3. DEFINITIONS

3.1 Abbreviations and acronyms used in this handbook.

a. ac – Alternating Current

b. AISC – American Institute of Steel Construction

c. ANSI – American National Standards Institute

d. ASTM – American Society for Testing and Materials

e. AWS - American Welding Society

f. C^4I – Command, Control, Communications, Computer, and Intelligence

g. C-E – Communications-Electronics

h. cw – Continuous Wave

i. dc – Direct Current

j. DID – Data Item Description

k. DISA – Defense Information Systems Agency

l. DNA – Defense Nuclear Agency

m. DoD - Department of Defense

n. DoDISS – Department of Defense Index of Specifications and Standards

o. EM – Electromagnetic

p. EMP – Electromagnetic Pulse

q. ESA – Electronic Surge Arrester

r. FWHM – Full Width at Half Maximum

s. FY – Fiscal Year

t. HAMS – Hardness Assurance, Maintenance, and Surveillance

u. HCA - Hardness Cricital Assembly

v. HCI – Hardness Critical Item

w. HCP – Hardness Critical Process

x. HEMP – High-Altitude Electromagnetic Pulse

y. HF – High Frequency

z. HM – Hardness Maintenance

aa. HM/HS – Hardness Maintenance/Hardness Surveillance

ab. HS – Hardness Surveillance

ac. HVAC – Heating, Ventilating, and Air Conditioning

ad. IEEE – Institute of Electrical and Electronics Engineers, Inc.

ae. LED – Light-Emitting Diode

af. MCP – Military Construction Program

ag. MEE – Mission-Essential Equipment

ah. MF – Medium Frequency

ai. MHD – Magnetohydrodynamic

aj. MIG – Metal Inert Gas

ak. MOV – Metal Oxide Varistor

al. NAVFACENGCOM - Naval Facilities Engineering Command

am. NEMA – National Electrical Manufacturers Association

an. NFPA – National Fire Protection Association

ao. O&S – Operations and Support

ap. PCI – Pulsed Current Injection

aq. PEA – Penetration Entry Area

ar. PMI - Preventive Maintenance and Inspection

as. POE – Point-Of-Entry

at. PP&B – Programming, Planning, and Budgeting

au. QA – Quality Assurance

av. QC – Quality Control

aw. rf – Radio Frequency

ax. RF I – Radio Frequency Interference

ay. rms – Root Mean Square

az. SCR – Silicon-Controlled Rectifier

ba. SE – Shielding Effectiveness

bb. SELDS – Shielded Enclosure Leak Detection System

bc. SGEMP – System-Generated Electromagnetic Pulse

bd. SPB – Special Protective Barrier

be. SPM – Special Protective Measure

bf. SPV – Special Protective Volume

bg. SREMP – Source-Region Electromagnetic Pulse

bh. TEMPEST – Compromising Emanations

bi. TEMPS – Transportable EMP Simulator

bj. TIG – Tungsten Inert Gas

bk. UHF – Ultrahigh Frequency

bl. UL – Underwriters Laboratory

bm. UPS - Uninterruptible Power Supply

bn. USACE – U.S. Army Corps of Engineers

bo. VHF – Very High Frequency

bp. V-I – Volt-Ampere

bq. VSWR – Voltage Standing Wave Ratio

br. WBC – Waveguide-Below-Cutoff

3.2 **Definitions.** Definitions for terms used in this handbook are taken from FED-STD-1037, where applicable.

a. **Absorption.** In the transmission of signals (electrical, electromagnetic, optical, acoustical), the conversion of transmitted energy into heat or other forms of energy.

b. **Absorption loss.** The attenuation of an electromagnetic wave as it passes through a shield. This loss is primarily due to induced currents and the associated power loss.

c. **Anode.** In the context of metal corrosion, the less noble or higher potential member of a pair of metals, upon which oxidation or corrosion occurs. Anode is the opposite of cathode.

d. **Anodizing.** Causing a metal, usually aluminum, to become oxidized on its surface to form a protective coating and prevent further corrosion. Anodizing is caused by an acid bath, usually sulfuric acid.

e. **Antenna.** Any structure or device used to collect or radiate electromagnetic waves.

f. **Aperture point-of-entry.** Intentional or inadvertent holes, cracks, openings, or other discontinuities in the facility HEMP shield surface. Intentional aperture points-of-entry are provided for personnel and equipment entry and egress and for fluid flow (ventilation and piped utilities) through the electromagnetic (EM) barrier.

g. **Arrester.** A device to protect an equipment, circuit, subsystem, or system from a voltage or current surge such as may be produced by lightning or an electromagnetic pulse.

h. **Bond.** The electrical connection between two metallic surfaces, established to provide a low-resistance path between them.

i. **Breakdown voltage.** The voltage at which an insulating material ceases to insulate and becomes electrically conductive.

j. **Broadband emission.** An emission which has a broad and continuous spectral energy distribution, so that the response of the measuring receiver does not vary significantly when tuned over a large bandwidth.

k. **Burnout.** A type of failure which implies the destruction of a component due to a permanent change beyond an acceptable amount in one or more characteristics.

l. **Cathode.** In the context of metal corrosion, the more noble or lower potential member of a metal pair, where reduction and practically no corrosion occurs.

m. **Cathodic protection.** Reduction or elimination of corrosion by means of direct current (de) that makes the metal to be protected a cathode, which is connected to another metal that serves as a sacrificial anode.

n. **Clamp.** A function by which the extreme amplitude of a waveform is reduced to a specified level.

o. **Clip.** To limit voltage or current amplitudes to a predetermined level.

p. **Common mode.** The voltage or current which is common to all signal-carrying conductors with respect to ground (also see differential mode).

q. **Common-mode rejection.** The ability of a device to reject a signal that is common to both its input terminals.

r. **Conducted interference.** Interference resulting from noise or unwanted signals entering a device by direct coupling.

s. **Continuous shield.** A shield fabricated from metal sheets or plates joined by welding, brazing, soldering, or other process so that all seams are completely filled with metal to form an electrically continuous joint.

t. **Corrosion.** A specific type of deterioration of a material, usually a metal, or its properties as a result of the surrounding environment.

u. **Coupling.** The means by which energy is transferred from one conductor (including a fortuitous conductor) to another.

v. **Damage (malfunction) level.** The value of voltage, current, or field strength that causes a permanent malfunction or damages an equipment item.

w. **Deliberate antenna.** A receiving or transmitting antenna specifically designed to be a part of a system, but which may pick up or receive HEMP energy as well (also see inadvertent antenna).

x. **Differential mode.** The voltage or current of a conductor with respect to any other conductor (also see common mode).

y. **Dissimilar metals.** Any combination of bare metals that are unlike. Metals are dissimilar when two metal specimens are in contact or otherwise electrically bonded together and generate an electric current. This current causes corrosion of one or both of the metal specimens. The more dissimilar the metals, the greater the galvanic attack of the anodic metal.

z. **Earth electrode subsystem.** A network of electrically interconnected rods, plates, mats, or grids installed or connected for the purpose of establishing a low-resistance contact with earth.

aa. **Electric protection.** The use of electrical devices and techniques to protect equipment, facilities, and people against hazardous voltages and currents.

ab. **Electric field.** A vector field around an electrically charged body. The field's strength at any point is the force that would be exerted on a unit positive charge at that point.

ac. **Electronic surge arrester (ESA).** A transient suppression device generally installed between an electrical terminal and ground. These devices respond to the rate of change and level of a current or voltage to prevent a rise above a predetermined value. The devices may include metal oxide varistors (MOVs), spark gaps, diodes, and others. ESAs are also known as electrical surge arresters, transient protection devices, and nonlinear devices. ESAs are used in conjunction with linear attenuation devices for electrical point-of-entry protection.

ad. **Electromagnetic barrier.** The topologically closed surface created to prevent or limit HEMP fields and conducted transients from entering the enclosed space. The barrier consists of the facility HEMP shield and point-of-entry treatments, and it encloses the protected volume.

ae. **Electromagnetic compatibility.** The ability of telecommunications equipment, subsystems, or systems to operate in their intended operational environments without suffering or causing unacceptable degradation because of electromagnetic radiation or response.

af. **Electromagnetic interference.** The phenomenon resulting when electromagnetic energy causes an unacceptable or undesirable response, malfunction, degradation, or interruption of the intended operation of an electronic equipment, subsystem, or system.

ag. **Electromagnetic pulse (EMP).** The electromagnetic radiation from a nuclear explosion caused by Compton-recoil electrons and photoelectrons from photons scattered in the materials of the nuclear device or in a surrounding medium. The resulting electric and magnetic fields may couple with electrical/electronic systems to produce damaging current and voltage surges. EMP may also be caused by nonnuclear means.

ah. **Electromagnetic radiation.** Radiation made up of oscillating electric and magnetic fields and propagated with the speed of light. Electromagnetic radiation includes gamma radiation; X-rays; ultraviolet, visible, and infrared radiation; and radar and radio waves.

ai. **Electromagnetic stress.** A voltage, current, charge, or electromagnetic field which acts on an equipment. If the electromagnetic stress exceeds the vulnerability threshold of the equipment, mission-aborting damage or upset may occur.

aj. **Equipotential ground plane.** A mass, or masses, of conducting material which, when bonded together, offers a negligible impedance to current flow.

ak. **Exclusion zone.** A region, inside a barrier, from which all cables and other conductors are excluded to ensure that they do not interact strongly with the HEMP fields in that region.

al. **Facility.** A building or other structure, either fixed or transportable in nature, with its utilities, ground networks, and electrical supporting structures. All wiring and cabling required to be provided are considered to be part of the facility. Any electrical and electronic equipment required to be supplied and installed are also part of the facility.

am. **Facility ground system.** The electrically interconnected system of conductors and conductive elements that provides multiple current paths to the earth electrode subsystem.

an. **Facility HEMP shield.** The continuous metallic housing that substantially reduces the coupling of HEMP electric and magnetic fields into the protected volume. The facility HEMP shield is part of the electromagnetic barrier.

ao. **Failure.** The termination of the ability of an item to perform its required function.

ap. **Far field.** The region of the field of a source where the angular field distribution is essentially independent of the distance from the source.

aq. **Fault.** In power systems, an unintentional short circuit or partial short circuit between energized conductors or between an energized conductor and ground.

ar. **Filter.** In electronics, a device that transmits only part of the incident energy and may thereby change the spectral distribution of energy.

as. **Free field.** An electromagnetic field in which the effects of boundaries are negligible over the region of interest.

at. **Galvanic corrosion.** Corrosion caused by placing two dissimilar metals in a corrosive or conductive solution in contact with each other, so that the potential difference allows electrons to flow between them.

au. **Galvanic series.** A listing of metals and alloys, ordered on their tendency to corrode independently in a particular electrolyte solution or other environment. This tendency for dissolution or corrosion is related to the electrical potential of the metal in a conductive medium, such as sea water. Metals closely positioned in the galvanic series will have similar electrical potentials, and corrosion will be minimized.

av. **Gas tube.** A spark gap with metal electrodes hermetically sealed in an envelope, so that a gas mixture and pressure can be controlled, thereby controlling the breakdown voltage of the device.

aw. **Global shield.** A single HEMP shield that encloses an entire building or the entire part of the building containing the mission-critical systems. Global shield is a synonym for overall shield.

ax. **Ground.** The electrical connection to earth through an earth electrode subsystem. This connection is extended throughout the facility via the facility ground system, consisting of the signal reference subsystem, fault protection subsystem, and lightning protection subsystem.

ay. **Hardness.** A measure of the ability of a system to withstand exposure to one or more of the effects of either nuclear or nonnuclear weapons.

az. **High-altitude electromagnetic pulse (HEMP).** An electromagnetic pulse produced at an altitude above the sensible atmosphere.

ba. **HEMP acceptance test.** An acceptance test is a test of a system, subsystem, or component performed to ensure that specified performance characteristics have been met. HEMP acceptance tests, conducted near the conclusion of a hardening construction or installation contract, are tests for the purpose of demonstrating that at least minimum performance requirements of the HEMP protection subsystem have been achieved before the subsystem will be accepted by the Government from the contractor.

bb. **HEMP hardness assurance.** Quality assurance measures during fabrication and installation of the HEMP protection subsystem for maintaining the integrity of the hardened design. HEMP hardness assurance is part of the total hardness assurance, maintenance, and surveillance (HAMS) program.

bc. **HEMP hardness critical assembly (HCA).** A top-level assembly of HEMP hardness critical items and other components, such as mounting brackets and fasteners, that may not be hardness critical. Hardness maintenance and surveillance actions are normally scheduled, performed, and tracked at the hardness critical assembly level.

bd. **HEMP hardness critical item (HCI).** A hardness critical item is an item, usually at the individual component level, having performance requirements for the purpose of providing protection from an explosion or natural disaster. Nuclear hardness critical items provide protection from environments produced by a nuclear event or are specially designed to operate under nuclear stresses. HEMP hardness critical items are the elements of the HEMP protection subsystem.

be. **HEMP hardness critical process (HCP).** A process, specification, or procedure which must be followed exactly to ensure that the associated HEMP hardness critical item attains its required performance.

bf. **HEMP hardness maintenance (HM).** Preventive maintenance (e.g., adjustments or cleaning) and corrective maintenance (e.g., repairs or replacements) on the HEMP protection subsystem or its hardness critical items and assemblies. These HM activities are intended to eliminate faults or to preserve specified performance levels.

bg. **HEMP hardness maintenance/hardness surveillance (HM/HS).** The combined preventive maintenance, inspection, test, and repair activities accomplished on a HEMP-protected operational facility to ensure that HEMP hardness is retained throughout the system life cycle. Hardness maintenance and hardness surveillance, along with hardness assurance, constitute a total HAMS program.

bh. **HEMP hardness surveillance (HS).** Inspections and tests of the HEMP protection subsystem or its hardness critical items and assemblies. These HS activities are intended to observe and monitor the condition and performance of the hardening elements and to detect faults.

bi. **High-speed gap.** A gas tube with improved response time produced by radioactive doping of the gas medium and the presence of a semiconductor triggering element across the gap.

bj. **Impulse ratio (of a spark gap).** The ratio of the actual sparkover voltage from an applied surge to the static sparkover voltage. The ratio is generally greater than or equal to one and increases with the increasing rate of rise of the applied voltage surge.

bk. **Inadvertent antenna.** Any physical object, other than deliberate antennas, that can act as a receiving antenna for HEMP energy.

bl. **Integrated logistics support.** A composite of all the support considerations necessary to ensure the effective and economical support of a system for its life cycle. It is an integral part of system acquisition and operation.

bm. **Internal coupling.** That part of the overall HEMP energy transfer process which occurs inside the protected volume, where fields penetrating the HEMP barrier induce currents traveling along cables or conductors inside this volume.

bn. **Intolerable upset.** An upset time of greater that n seconds, identified as part of the facility operational mission requirements.

bo. **Life-cycle cost.** The total direct, indirect, recurring, nonrecurring, and other related costs incurred or estimated to be incurred in the design, development, production, operation, maintenance, and support of a major system over its anticipated useful life.

bp. **Lightning down conductor.** The conductor connecting the air terminal or overhead ground wire to the earth electrode subsystem.

bq. **Low-risk HEMP hardening.** A hardening technique that features a high-quality electromagnetic barrier with minimized and protected points-of-entry. Virtually all mission-essential communications-electronics and support equipment are placed in the protected volume enclosed by the barrier and operate in a relatively benign electromagnetic environment, isolated from the external HEMP stresses. The low-risk approach results in a well-defined HEMP protection subsystem configuration with inherent testability.

br. **Magnetic field.** A vector field set up by a moving charge or current. This field also exerts a force on moving charges or currents within the field.

bs. **Mission-critical system.** Synonym for mission-essential equipment.

bt. **Mission-essential equipment (MEE).** Includes all communications-electronics and support equipment required to perform specified missions. In the context of MIL-STD-188-125 and this handbook, MEE refers to equipment required to perform missions specified to be hardened against the HEMP environment.

bu. **National Electrical Code®.** A standard governing the use of electrical wire, cable, and fixtures installed in buildings; developed by a committee of the American National Standards Institute, sponsored by the National Fire Protection Association (NFPA), identified by the description ANSI/NFPA 70, and adopted by the Federal Government.

bv. **Near field.** The region of the field of an antenna between the close-in reactive field region and the far-field region. The angular field distribution is dependent upon distance from the antenna in the near field.

bw. **Noise.** An undesired disturbance within the useful frequency band. Noise is the summation of unwanted or disturbing energy introduced into a communications system from man-made and natural sources.

bx. **Norms.** Scalar quantities which characterize the features of a complicated waveform. Norms used as pass/fail criteria for pulsed current injection test residual internal stresses are peak current, peak rate of rise, rectified impulse, and root action.

by. **Operational upset.** Usually implies temporary impairment of operation that will not result in permanent damage, such as a significant disturbance or perturbation to the normal operation.

bz. **Overall shielding.** As used in this handbook, the protection of an entire facility by use of a single shielded enclosure. An overall shield is a central requirement of the low-risk hardening approach.

ca. **Peak current.** The peak current norm of a current waveform *I(t),* in units of amperes, is the maximum absolute value of *I(t)* over times from $t = 0$ to $t = 5 \times 10^{-3}$s. At the start of the pulsed current injection drive pulse, $t = 0$.

cb. **Peak rate of rise.** The peak rate of rise norm of a current waveform *I(t),* in units of amperes per second, is the maximum absolute value of dI/dt over times from $t = 0$ to $t = 5 \times 10^{-3}$s. At the start of the pulsed current injection drive pulse, $t = 0$.

cc. **Penetrating conductor.** Any electrical wire or cable or other conductive object, such as a metallic rod, which passes through the electromagnetic barrier. Penetrating conductors are also called conductive points-of-entry.

cd. **Penetration.** The passage through a partition or wall of an equipment or enclosure by a wire, cable, or other conductive object.

ce. **Penetration entry area (PEA).** That area of the electromagnetic barrier where long penetrating conductors (such as an electrical power feeder) and piping points-of-entry are to be concentrated.

cf. **Permeability.** A general term used to express various relationships between magnetic induction and magnetizing force; the magnetic analog of electrical permittivity. Either absolute permeability or relative permeability may be used. The permeability of free space (magnetic constant) is made up of corresponding values of magnetizing force and flux density.

cg. **Permittivity.** The scalar that relates the electric field strength to the electric flux density. Permittivity is also known as dielectric constant. Permittivity is analogous to

magnetic permeability, and it specifies the ease with which electric flux is permitted to pass through a given dielectric material.

ch. **Plane wave.** An electromagnetic wave that predominates in the far-field region of an antenna, and with a wavefront that is essentially in a flat plane. In free space, the impedance of a plane wave is 377 ohms.

ci. **Point-of-entry (POE).** A location on the electromagnetic barrier where the shield is penetrated and HEMP energy may enter the protected volume unless an adequate POE protective device is provided. POEs are classified as aperture POEs or penetrating conductors according to the type of penetration. They are also classified as architectural, mechanical, structural, or electrical POEs according to the architectural-engineering discipline in which they are usually encountered.

cj. **POE protective device or POE treatment.** The protective measure used to prevent or limit HEMP energy from entering the protected volume at a POE. Common POE protective devices include waveguides-below-cutoff (WBCs) and closure plates for aperture POEs, and filters and ESAs on penetrating conductors.

ck. **Pulsed current injection (PCI).** A test method for measuring performance of a POE protective device on a penetrating conductor. A HEMP threat-relatable transient is injected on the penetrating conductor at a point outside the electromagnetic barrier, and the residual internal transient stress is measured inside the barrier.

cl. **Radio frequency (rf).** Those frequencies of the electromagnetic spectrum normally associated with radio wave propagation.

cm. **Radio frequency interference (RFI).** Synonym for electromagnetic interference.

cn. **Rectified impulse.** The rectified impulse norm of a current waveform *I(t),* in units of ampere-seconds, is defined by the equation

$$\text{Rectified impulse} = \int_{0}^{5\times10^{-3}\,\mathrm{s}} \left|I(t)\right| dt \qquad (1)$$

where $t = 0$ at the start of the PCI drive pulse.

co. **Residual internal stresses.** The electromagnetic fields, voltages, currents, or charges which originate from the HEMP environment and penetrate into the protected volume after attenuation by elements of the electromagnetic barrier.

cp. **Retrofit HEMP hardening.** A retrofit action is an action taken to modify in-service equipment. Retrofit HEMP hardening is the installation or substantial upgrade of the HEMP protection subsystem for an existing facility or equipment.

cq. **Root action.** The root action norm of a current waveform *I(t),* in units of amperes-$\sqrt{\text{seconds}}$, is defined by the equation

$$\text{Root action} = \sqrt{\int_0^{5\times10^{-8}\text{s}} I^2(t)\,dt} \tag{2}$$

where $t = 0$ at the start of the PCI drive pulse.

cr. **Shield.** A housing, screen, or cover that substantially reduces the coupling of electric and magnetic fields into or out of circuits or prevents the accidental contact of objects or persons with parts or components operating at hazardous voltage levels.

cs. **Shielding effectiveness (SE).** A measure of the reduction or attenuation in the electromagnetic or electrostatic field strength at a point in space, caused by the insertion of a shield between the source and that point.

ct. **Simulation equipment.** The equipment used to simulate the threat environment, including pulsers and current drivers.

cu. **Spark gap.** A voltage limiting or clamping device (an ESA) consisting of two or more electrodes separated by a dielectric. An electric arc develops whenever the voltage between two electrodes exceeds the sparkover voltage. Examples are the carbon-block gap and the gas tube.

cv. **Special protective measure (SPM).** All HEMP hardening measures required in addition to implementation of the electromagnetic barrier. Special protective measures are necessary for MEE outside the barrier, for MEE which is within the protected volume and experiences damage or upset during verification testing, and in cases requiring a special protective volume.

cw. **Special protective volume (SPV).** A region within the electromagnetic barrier and a special protective barrier (SPB), where electromagnetic stresses due to HEMP may exceed the residual internal stress limits for the protected volume. The SPB may be a separate shield with protected penetrations; more commonly, shielded cables or conduits and equipment cabinets and closed piping systems are used to provide the needed electromagnetic isolation from the protected volume.

cx. **Strength.** The electromagnetic strength of an electronic subsystem or equipment is the peak value of an electromagnetic stress, such that the subsystem/equipment will continue to operate without damage or intolerable upset. The difference between equipment strength and electromagnetic stress is known as the strength margin. Tested margins are applicable only in the hardening of MEE outside the low-risk barrier.

cy. **System state.** A particular configuration of a system by virtue of the position or state of each switch, circuit breaker, solid-state digital device, or other multistate circuit device; or by virtue of the mechanical configuration of doors, equipment, or machines that make up the system. External states include solid-state logic outside the facility barrier, the position of external switches, and configurations of mechanical devices outside the HEMP barrier. Internal states are determined by the configurations of mechanical devices inside the HEMP barrier or by particular circuit connections realized when such things as switches, circuit breakers, thermostatic control, pressure controls, and door interlocks are in a particular on/off arrangement, and electronic states occurring within the system.

cz. **Transient.** Short-time variation outside of steady state conditions in the characteristics of power delivered.

da. **Transient upset.** A term used to describe an undesired system effect or degradation induced by a short-duration or transient excitation. The term frequently is used to cover all types of such undesired HEMP effects that are not considered to be permanent damage.

db. **Upset.** The impairment of proper system operation that is not due to burnout or other permanent damage to one or more components. Systems that have been upset may return spontaneously to proper operation or may require some operator action, such as resetting a circuit breaker or reloading information into memory.

dc. **Varistor.** A nonlinear resistance device (e.g. ESA) in which current varies as a function of the applied voltage, thereby acting as a limiter. Examples are the silicon carbide resistor and the metal oxide varistor.

dd. **Verification testing.** Tests conducted for demonstrating that the installed HEMP protection subsystem provides the required HEMP hardness. They are performed after the construction and acceptance testing are complete and after the equipment is installed and functioning, to determine if the operational system suffers mission-aborting damage or upset due to simulated HEMP excitations. Verification is normally a Government-conducted test, and is not part of a facility construction contract.

de. **Waveguide-below-cutoff.** A metallic waveguide whose primary purpose is to attenuate electromagnetic waves at frequencies below the cutoff frequency (rather than propagating waves at frequencies above cutoff). The cutoff frequency is determined by the transverse dimensions and geometry of the waveguide and properties of the dielectric material in the waveguide.

df. **Waveguide cutoff frequency.** The frequency below which electromagnetic energy will not efficiently propagate in a waveguide.

dg. **Zener diode.** A reverse-breakdown diode whose breakdown voltage is caused by tunneling or field emission of charge carriers in the depletion layer. These diodes are sometimes used as ESAs.

4. HOW TO USE THIS HANDBOOK

4.1 **Introduction.** This handbook is directed toward architect-engineers and project managers who are responsible for designing, building, testing, and maintaining the HEMP protection of mission-essential equipment in a fixed facility. The handbook describes the methods available to verify that the HEMP protection for the facility is adequate. It explains the requirements of MIL-STD-188-125, and presents clarifying descriptions, background information, procedural suggestions, and illustrations to explain the concepts and processes of HEMP protection. Materials, methods, and devices needed to design, construct, test, and maintain HEMP protection from initial conception to deactivation of a fixed facility are also described.

It should also be noted that the handbook discussions are generally restricted to HEMP protection issues. Conventional system requirements that are not HEMP-related and compliance with national, state, local, and commercial codes and standards are not addressed. The facility designs including those for the HEMP hardening elements must therefore be engineered by the architect-engineer and mechanical, structural, and electrical specialists to satisfy these additional requirements. They should work closely with a qualified HEMP designer to ensure that the HEMP hardness, reliability, maintainability, and testability y are preserved and that life-cycle costs are minimized. For these reasons, the handbook figures should be considered only as illustrations of the HEMP protection principles; they are not intended for use as construction drawings.

4.2 **Handbook content.** A short description of the contents of each section and appendix is presented below:

a. Section 5 is a brief tutorial on the physical origins of HEMP, for those who are interested in the nature of the HEMP threat.

b. Section 6 defines the concepts of low-risk HEMP protection for equipment in fixed facilities and illustrates ways to develop the appropriate HEMP barrier topology in a facility.

c. Sections 7 through 12 discuss development of the barrier topology [7], design and construction of the HEMP shield [8], design and installation of HEMP protection for architectural openings (doors and hatches) [9], mechanical apertures (pipes and air passages) [10], structural openings (building supports) [11], and electrical penetrators (power, communication, control, and radio frequency wiring) [12].

d. Section 13 briefly discusses the influence of grounding and bonding methods on HEMP protection.

e. Section 14 discusses the three types of SPMs and how to design and construct them.

f. Section 15 is devoted to corrosion and its mitigation. This is an important topic for the life-cycle reliability of HEMP shields and the protective measures that are used in the openings in the shield.

g. Section 16 presents inspections and tests for the various HEMP protection features. It includes the acceptance and verification testing required by MIL-STD-188-125, as well as other inspections and tests that have been found to be useful.

h. Sections 17, 18, and 19 present discussions of some of the supporting disciplines related to HEMP protection in facilities. These disciplines are reliability and maintainability, testability, human engineering, and configuration control.

i. Section 20 is devoted to hardness maintenance and hardness surveillance of HEMP protection subsystems.

j. Section 21, devoted to HEMP program management, includes recommendations for ensuring that HEMP protection efforts are coordinated throughout all phases of the facility life.

k. Appendix A is a sample construction specification for a HEMP protection subsystem, partially based upon specifications that have been used successfully for existing programs. This sample specification can be adapted for use on future construction projects.

l. Appendix B contains some representative cost information gathered from documentation on recently built facilities that incorporate HEMP protection.

m. Appendix C lists data item descriptions applicable to HEMP program documents.

4.3 **Handbook arrangement.** This handbook presents HEMP protection guidelines, both previously published and new, in a format designed to allow quick access to specific information required by the user.

Sections 7 through 21 of this handbook are, for the most part, written following the general format: basic principles; MIL-STD-188-125 requirements; applications; and references.

In each section, after basic principles of the subject are introduced and described, the requirements of MIL-STD-188-125 are quoted. The quotes include paragraph, table, and figure numbering as they exist in the standard, plus the applicable figures and tables. Each quote is enclosed in a frame and printed in a different type style to distinguish the requirements from handbook information. Following the standard quotes, these requirements are explained and expanded to help the designer apply the principles to meet the intent of the standard. Some of the topics included under the section subheadings are as follows:

a. Basic principles

- Functional descriptions
- Governing equations

b. MIL-STD-188-125 requirements

- MIL-STD-188- 125 requirements, with explanations and reasons for these requirements

c. Applications

- Design options—ways to meet each requirement
- Tradeoff parameters—how to choose among the options
- Guidelines and practices to meet the requirements
- Preferred methods and devices
- Selected examples at HEMP-hardened fielded facilities
- Good practices that may not be required by the standard
- Guidance for writing specifications for this item or subject

d. References

4.4 **Guide to the HEMP protection program.** Figure 1 is intended to give the reader a sense of the overall HEMP protection program. This figure is a flowchart that shows the major steps necessary to protect vital equipment from HEMP effects. What may at first appear to be a complex process is actually a straightforward sequence of tasks to be accomplished during a facility's lifetime. The dashed rectangles in figure 1 correspond to the six major phases in the life cycle of HEMP protection in a fixed facility. These phases are planning, programming, and budgeting; design and specification development;

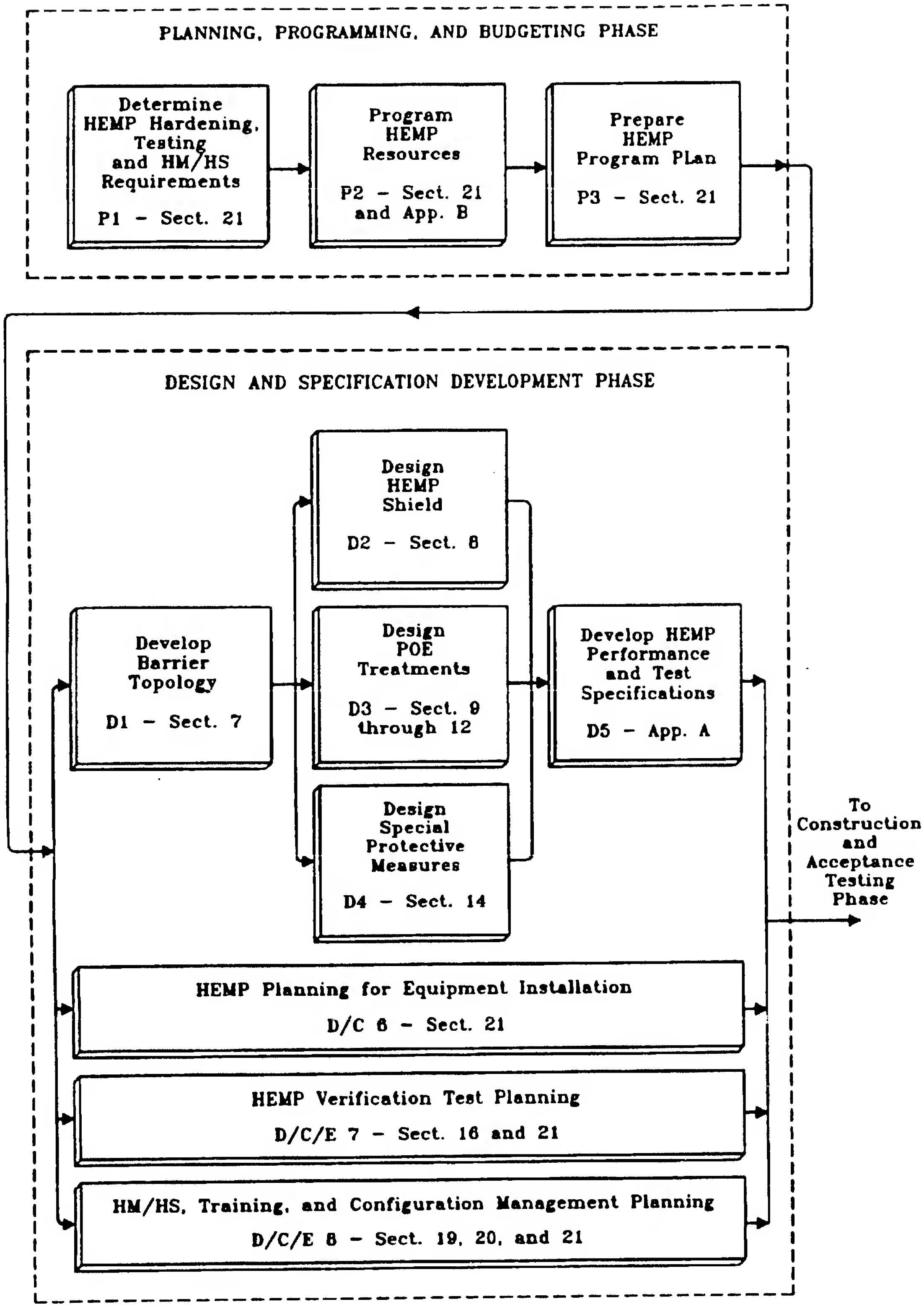


FIGURE 1. **Overview of HEMP protection in facilities.**

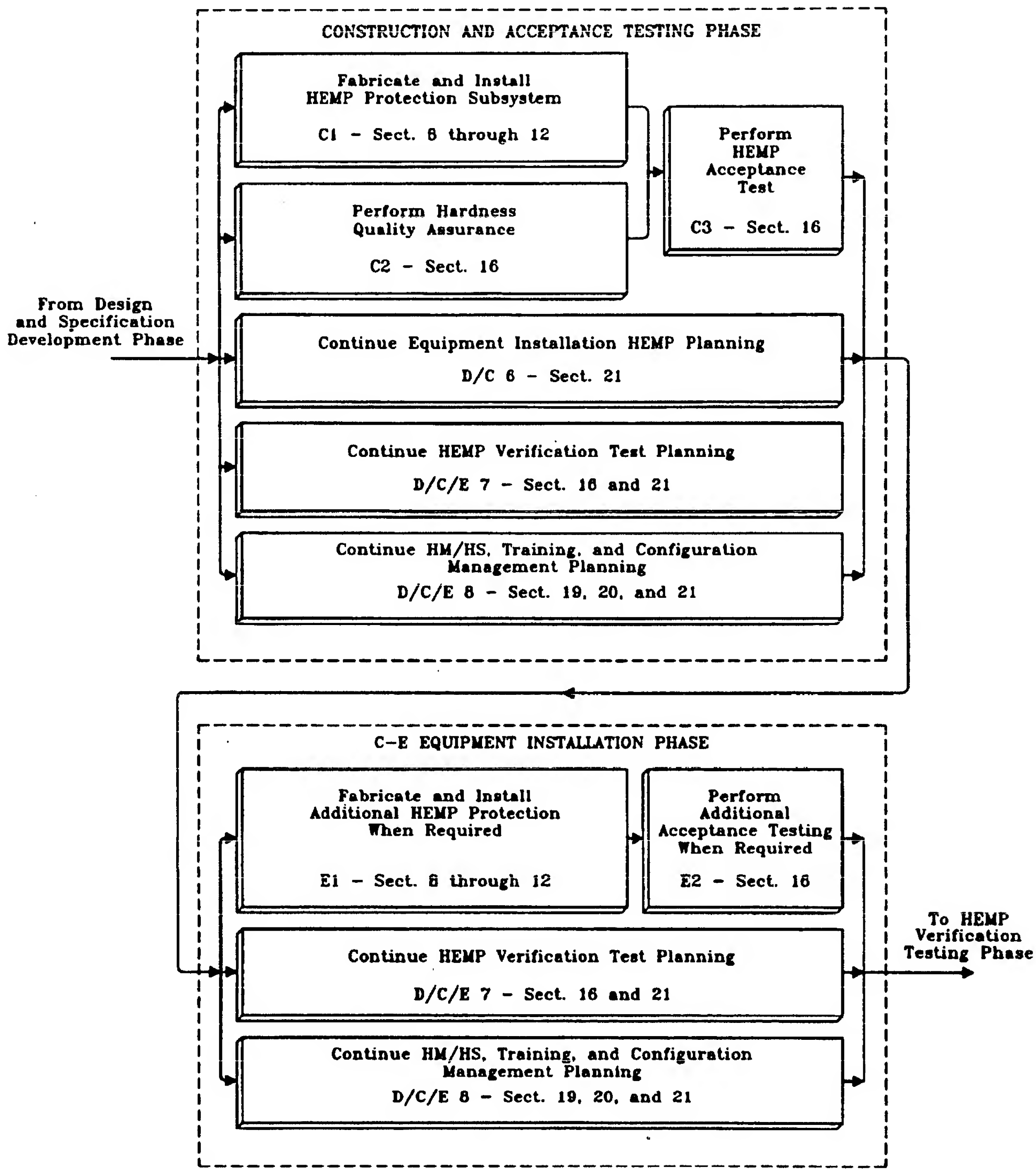


FIGURE 1. **Overview of HEMP protection in facilities (continued).**

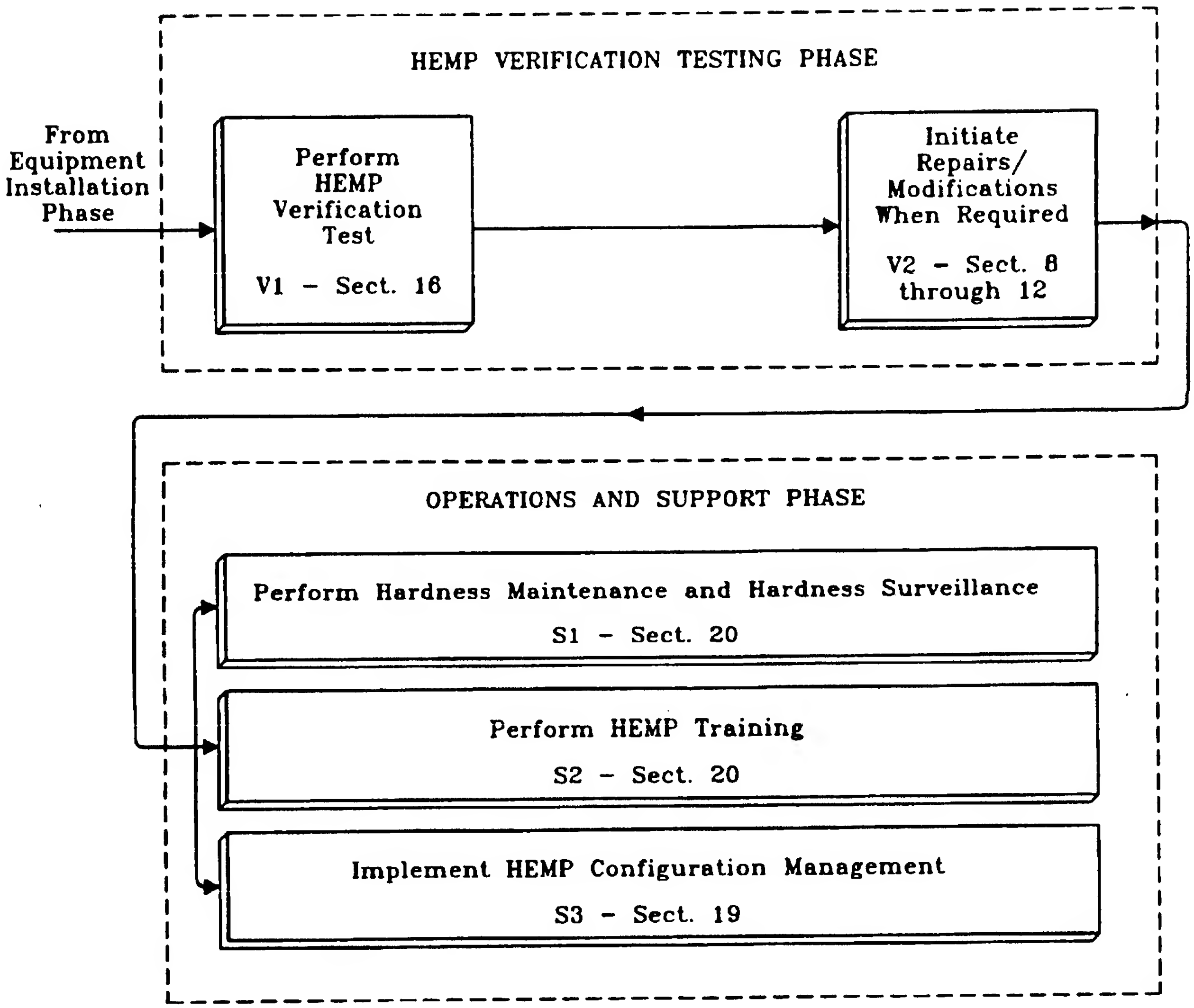


FIGURE 1. **Overview of HEMP protection in facilities (continued).**

construction and acceptance testing; communications-electronics (C-E) equipment installation; HEMP verification testing; and operations and support. Each task, shown in a solid rectangular box, includes a reference symbol such as PI and a section reference such as section 21. The reference symbol directs the reader to a brief description of the task, to be found in subsection 4.5. The section references are to handbook sections that contain expanded information.

A more detailed version of the life-cycle diagram and additional descriptions of the tasks from the program management perspective are presented in handbook section 21.

Some unfamiliar terms and abbreviations may be noted in figure 1, such as electromagnetic barrier, POE, and special protective measures. These terms are briefly defined in section 3 of this handbook and are described more completely in the referenced handbook sections. The terms are also defined in MIL-TD-188-125.

4.5 Brief description of HEMP protection program tasks. Figure 1 shows six phases in the life cycle of a facility. These phases are programming, planning, and budgeting; design and specification development; construction and acceptance testing; C-E equipment installation; HEMP verification testing; and operations and support. Only the verification testing phase is unique to HEMP-hardened facilities.

The task reference symbols used in the HEMP life-cycle diagram represent the following:

a. Planning, programming, and budgeting phase.

- P1 – Determine HEMP hardening, testing, and HM/HS requirements. This first task involves the determination of tram- and post-HEMP attack missions of the facility and the designation of mission-essential equipment required to perform those missions. Based upon the outcome of this step, a HEMP hardening approach-presumed in the handbook to be the approach prescribed in MIL-TD-188-125--is developed and specified in the facility requirements documentation. The facility requirements document is the formal identification of the requirements that must be satisfied for the building to fulfill its intended purposes. At the same time that the hardening approach is defined, the HEMP verification and HM/HS concepts are developed. Section 21 describes the requirements definition process.

- P2 - Program HEMP resources. This task represents the initial step to obtain funding for design and construction of the HEMP protection subsystem, for ver-

ification testing, and for operation and maintenance of the hardening elements. HEMP costs are integrated with other program costs and submitted as part of the normal military budgeting process. Section 21 contains simple algorithms that can be used for this purpose until more detailed estimates are generated, and appendix B summarizes the data on which the algorithms are based.

- **P3 – Prepare HEMP program plan.** The HEMP program plan, which is discussed in section 21, is a planning document to identify HEMP program tasks and to assign responsibilities for performing the required actions. A brief description of the work is provided, and guidance references are listed. A milestone schedule is also established.

b. **Design and specification development phase.**

- **D1 – Develop HEMP barrier topology.** The topology of the HEMP barrier, or barriers, is the single biggest factor in the design, cost, and difficulty of construction and testing of HEMP protection in the facility. This topology refers to the shape of the HEMP barrier, where it is in relation to the building's structure, and what equipment is to be enclosed within the HEMP barrier. The topology also defines the HEMP interaction paths, points-of-entry of energy, and the HEMP protection devices used to ensure protection. Section 7 describes this determination in detail.

- **D2 – Design HEMP shield(s).** The largest physical portion of the HEMP barrier is the metal shield(s). Once the barrier topology has been determined, the shield(s) can be designed along with the rest of the facility as explained in section 8. The shield design must be closely coordinated with the design of the building structure. Reliability, maintainability, testability, human engineering, and safety considerations in the design of a shield and other HEMP protection elements are addressed in sections 17 and 18. The POEs are located and appropriate accommodations are provided. The shield(s) must be designed and constructed to allow access for hardness assurance, maintenance, and surveillance. The term shield(s) is used to emphasize that more than one protected volume may be required.

- **D3 – Design POE treatments.** Every barrier POE must be provided with appropriate penetration protection devices. After the overall shield design has begun, HEMP protective designs for the shield openings can be developed. POES are classified as architectural, mechanical, structural, and electrical according to the

architectural-engineering discipline in which they are usually encountered. Hardening treatments for the four classes of penetrations are addressed in sections 9, 10, 11, and 12, respectively.

- **D4 – Design special protective measures.** In some cases, equipment cannot be enclosed within the normal HEMP barrier and still function properly. Section 14 presents cases where special treatment is required. These instances, with equipment such as high-frequency radios and heat exchangers, complicate the design of the HEMP protection subsystem. They should be factored into the barrier design as early as possible to avoid redesign and rework.

- **D5 – Develop HEMP performance and testing specifications.** The design drawings and project specifications are the binding documents on the building construction contractor, with the specifications having the higher priority in the event of conflict. Performance requirements for the HEMP shield, POE protective devices, and HCIs used as special protective measures must therefore be explicitly written into the specifications. Similarly, the contractor is obligated to conduct only those tests that are explicitly required by the specifications. Citation of MIL-STD-188-125 as an "applicable publication," in the absence of such supporting language, does not impose the performance and test requirements of the standard. A sample construction specification presented in appendix A provides guidance for preparing this document.

- **D/C6 – HEMP planning for equipment installation.** Most HCIs will be procured and installed under the building construction contract. However, components such as rf waveguide penetrations and antenna line POE protective devices, which must be matched to the particular C-E system, may be provided in the equipment installation phase. These HEMP hardening features should undergo the same careful design and review processes as the building HCIs. The D/C prefix of the reference symbol implies that the task begins during the design phase and continues through building construction.

- **D/C/E 7 – HEMP verification test planning.** The HEMP verification test program will be conducted to demonstrate the facility hardness as soon as practical after the C-E equipment is installed and functioning. Test methods to be used are discussed in handbook section 16, and section 21 contains an outline for the detailed verification test plan. This planning task includes development of the procedures and all other pretest activities. Through participation in the design, construction, and equipment installation phases, the test agency acquires an

intimate knowledge of the HEMP protection subsystem configuration and the familiarity with site mission operations necessary for preparing the test plan.

- **D/C/E 8- HM/HS, training, and configuration management planning.** The technical manuals, training materials, spares and supplies, and special tools and test equipment required for life-cycle maintenance of the HEMP protection subsystem are provided under this planning task. Configuration management guidance is presented in section 19. Training, hardness maintenance, and hardness surveillance are addressed in section 20, and the recommended outline for a comprehensive HEMP protection subsystem technical manual appears in section 21. Principles and methods of the traditional integrated logistics support discipline are employed.

c. **Construction and acceptance testing phase.**

- **C1 - Fabricate and install HEMP protection subsystem.** The final design drawings for the building and the performance and test specifications (see D1 through D5) are packaged into an invitation for bids, and a construction project contract is awarded. The successful contractor prepares submittals required by the specifications, procures components and materials, and constructs the building in accordance with the approved design. Government representatives review and approve the submittals and proposed change orders and perform a construction surveillance function. Fabrication and installation of the HEMP protection subsystem will be included in this building construction effort for most MIL-STD-188-125 hardened facilities.

- **C2 – Perform hardness quality assurance.** The hardness assurance program is implemented in parallel with construction activities to ensure that HEMP protection subsystem components, materials, and processes will comply with performance requirements of MIL-STD-188-125. These procedures, including 'in-factory" tests of purchased HCIs and "in-progress" weld inspections, are vital to the construction of an effective electromagnetic barrier. Defects are identified while the contractor's crew is still on site, and repairs can be made with minimum cost and schedule impacts. Section 16 discusses some of the recommended methods for performing this quality assurance.

- **C3 – Perform HEMP acceptance test.** HEMP acceptance tests on the shield, POE protective devices, and special protective measures represent the proof to the Government that the building construction contractor is delivering a satisfactory end product. Acceptance test procedures required by MIL-STD-

188-125 are discussed in section 16, and section 21 addresses related HEMP program management aspects. The handbook strongly recommends that the acceptance procedures be performed by an independent contractor, hired by the Government, and be witnessed by a qualified Government inspector. In the event of failures, flaws must be corrected by the building contractor and retested satisfactorily before the final payment is made.

d. **Communications-electronics equipment installation phase.**

- **El - Fabricate and install additional HEMP protection, when required.** This task applies when additional HEMP hardening devices are provided as part of the communications-electronics equipment installation. It is virtually identical to task Cl, except for the limited scope and the different organization responsible for performing the work. HCIs supplied during this phase must comply with the same MIL-STD-188-125 requirements as those installed by the building construction contractor.

- **E2 – Perform additional acceptance testing, when required.** The HEMP acceptance test requirements are equally applicable to HCIs installed by the building contractor and to those provided by the equipment installation contractor. Only new devices and HEMP protection subsystem modifications subsequent to building acceptance must be tested at this time.

e. **HEMP verification testing phase**

- **V1 – Perform HEMP verification test.** This set of tests, described in section 16, constitutes the pass/fail point for the entire HEMP protection acquisition sequence. The verification program determines whether the as-built facility and the as-installed MEE provide the operationally required, hardened mission capabilities established in the first step of the process (see Pi). Testing is performed in accordance with the detailed test plan developed under task D/C/E 7. It includes measurements of HEMP protection subsystem performance and equipment operation in the presence of simulated HEMP excitations to verify that mission-aborting damage or upsets do not occur. A definitive statement on the HEMP hardness of critical, time-urgent functions and a list of deficiencies (if applicable) must be provided as the end product of the verification effort.

- **V2– Initiate repairs/modifications, when required.**All deficiencies identified by the verification test program must be corrected, retested, and shown to provide the required hardness. There are two types of HEMP protection subsystem

verification test failures. The first category consists of a hardening element that does not exhibit the specified performance: a shield with less than the required shielding effectiveness; an electrical POE protective device that allows excessive residual internal transients; or an HCI used as a special protective measure with in-situ performance below the design value. Appropriate repairs must be made in these cases. The second category of failure is the occurrence of mission-aborting damage or upset, even though all HCIs meet the MIL-STD-188-125 requirements. In this latter instance, additional SPMs must be designed, implemented, and demonstrated.

f. **Operations and support phase**

- **S1 – Perform hardness maintenance and hardness surveillance.** The HEMP protection subsystem technical manual, developed under task D/C/E 8, will contain the procedures to be performed during the operations and support phase. As discussed in section 20, these procedures fall into four general categories: preventive maintenance-cleaning, adjustments, and periodic replacements of HCIs; organizational surveillance-performance checks and inspections done by site maintenance personnel; corrective maintenance-repair of faults in the HEMP protection subsystem; and periodic hardness surveillance/reverification testing—HEMP testing requiring simulation equipment, instrumentation, and expertise that are generally not available on site. This task also includes initiation of changes to the HM/HS technical manual whenever the need for improvements is recognized.

- **S2 – Perform HEMP training.** Many of the deficiencies typically observed during hardened facility surveys are the result of unintentional violations of the topology by personnel unfamiliar with principles and practices of HEMP protection. This type of problem can be virtually eliminated with an adequate training program. New personnel reporting to the staff should be briefed on the hardening requirements and their role in preserving the hardness. The HEMP program manager and leading maintenance personnel should receive more extensive training, possibly in a school environment. Finally, periodic training sessions should be conducted on site to reemphasize HEMP awareness and to address site-specific issues and problems. Training recommendations are discussed in handbook section 20.

- **S3 – Implement HEMP configuration management.** The HEMP configuration management program is intended to prevent uncontrolled changes to the HEMP

protection subsystem and to ensure that hardness impacts are properly considered in all planned facility modifications. Major retrofits and additions are very common during the lifetime of a facility. The HEMP protection in such modifications must be designed, constructed, tested and maintained in the same manner as the hardening provided in the original project. Section 19 presents guidelines for configuration management.

5. THE HEMP ENVIRONMENT AND SYSTEM RESPONSE

5.1 **Introduction.** The detonation of a nuclear device in or above the earth's atmosphere produces an intense, time-varying electromagnetic field (electromagnetic pulse or EMP). The EMP environment produced by an exoatmospheric event is a result of the deposition of device energy, chiefly by gamma rays, in the atmosphere at altitudes between 20 km and 40 km. The HEMP environment then propagates, with little attenuation, to all points in the air or on the ground within line-of-sight of the burst. As indicated in figure 2, a single high-altitude burst can produce high-amplitude HEMP fields over millions of square kilometers on the earth's surface, The HEMP field can rise to a peak value of about 50 kV/m within a few nanoseconds; it then decays gradually over a period lasting hundreds of seconds.

Other forms of EMP environments are produced by detonations at different altitudes and experienced by systems at different locations with respect to the burst. Source-region electromagnetic pulse (SREMP) is characterized by intense, time-varying electron currents and air conductivity, as well as electromagnetic fields, and is produced in any circumstance in which a system is exposed to a garoma flux greater than about 10^4 grays/second. Thus, the detonation of a nuclear device at or near the earth's surface can impose an SREMP environment on a ground-based system. A missile system in the boost phase of flight can also experience SREMP as it passes through the source region from either a high-altitude or endoatmospheric burst.

Another important form of EMP environment is produced by direct interaction of X-ray, gamma, and neutron ionizing radiation with a system under vacuum or near-vacuum conditions. This form of EMP is known as system-generated electromagnetic pulse (SGEMP), and it principally applies to satellites, missiles, and reentry vehicles in midcourse flight.

MIL-STD-188-125 (reference 5-1) and this handbook are concerned with protecting ground-based systems only against the HEMP environment. This is because HEMP is the only nuclear environment which most ground-based systems are likely to experience and the only nuclear environment which can be imposed on many systems simultaneously with the expenditure of very few weapons.

The HEMP environment constitutes a threat to the operation of electronic systems inasmuch as the HEMP fields induce electrical current and voltage stresses on and within systems. These HEMP-induced stresses can cause systems to malfunction due to circuit

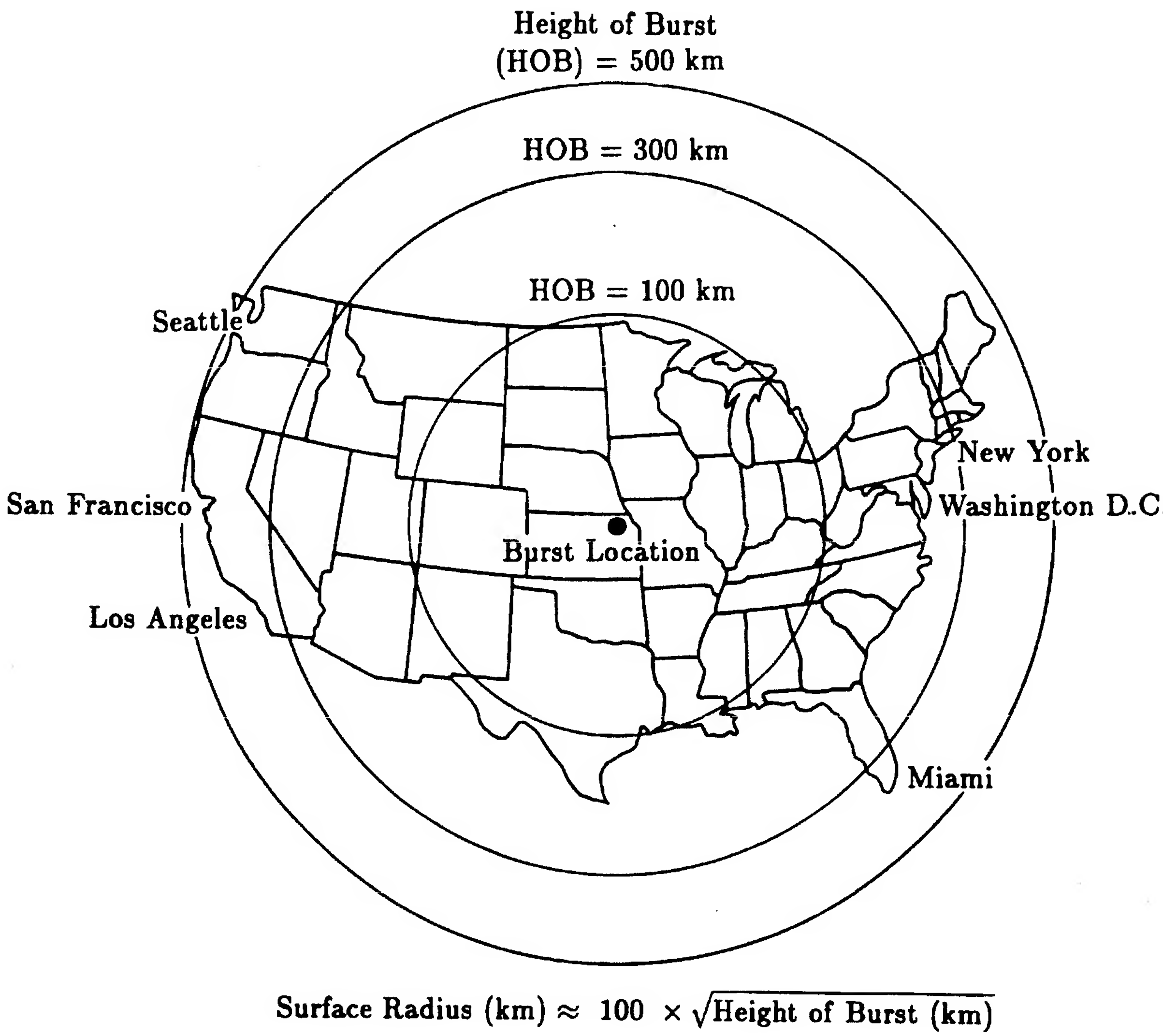


FIGURE 2. **HEMP ground coverage for bursts at various heights.**

damage or upset. HEMP-induced stresses can also ignite electroexplosive devices or fuel stores.

The HEMP environment is but one of several electromagnetic environments that critical defense systems must be able to withstand. Other environments include electromagnetic interference, electrostatic discharge, lightning, and radio frequency or microwave energy weapons. The HEMP threat to systems, however, is unique in a number of respects. The spatial coverage of the HEMP environment is such that many systems, including entire communication networks, can be nearly simultaneously exposed to high-level electrical stresses. Consequently, strategies for dealing with electromagnetic threats that depend on system outages being few and localized, such as use of switched networks, redundancy, and replacement of damaged parts with spares, may not provide adequate protection from HEMP.

In addition to the differences in spatial coverage, the HEMP fields exceed most other hostile environments in terms of time-domain and frequency-domain intensities. The HEMP environment rises more rapidly than do most other threats and, hence, has more high-frequency content. The high frequencies can propagate past protective devices which provide adequate protection against more slowly varying signals. Conversely, the HEMP environment includes low-frequency components that can pass through many protective devices without attenuation. Finally, the HEMP environment, unlike most other electromagnetic threats, is not commonly experienced in peacetime. As a result, potentially susceptible system components may not be identified and replaced in the course of routine system operation, as they often are for other threats.

Because of these unique features, special measures must be taken to protect systems against HEMP and to ensure that the protection will be adequate when needed. The measures required for HEMP-hardening critical, time-urgent, ground-based facilities are specified in MIL-STD-188-125.

The remainder of this section reviews the following topics:

a. The history of recognition of the HEMP threat, with emphasis on the threat to ground-based systems (see 5.2)

b. The physical processes involved in the generation of the HEMP environment and the principles underlying formulation of the standard HEMP environment as presented in DoD-STD-2169 (reference 5–2) (see 5.3)

c. System response to HEMP (see 5.4)

5.2 **History of recognition of the HEMP threat.** The major events in developing the current understanding of the HEMP environment and the threat posed to ground-based systems are identified in table I. That nuclear explosions would generate electromagnetic signals had been anticipated before the first nuclear event, TRINITY, and the existence of EMP from atmospheric bursts was well established by the mid-1950s on the basis of experimental observations during atmospheric nuclear testing. Theoretical explanations and predictive models of EMP from atmospheric bursts began to appear in the 1950s. Concerns developed over the possible coupling of EMP fields to cables leading into military systems.

In the early 1960s, attempts were made to model and predict the EMP that would be produced by high-altitude bursts. These early theoretical efforts were motivated by an interest in the use of HEMP signals for burst detection and weapon diagnostic purposes. However, during the FISHBOWL high-altitude tests, the actual signals greatly exceeded the predictions. As a result, many of the measurements were driven off scale. The FISHBOWL test results were the first indications of the severity of the HEMP environment. Intense efforts to understand the HEMP environment and to investigate the possible effects of HEMP fields on systems followed.

In 1963, Longmire proposed a model to explain the FISHBOWL test data (reference 5–3). In this model, the peak HEMP fields are produced by the turning of Compton recoil electrons in the earth's magnetic field. In 1964, Karzas and Latter formulated a mathematical theory and approximation for predicting the HEMP fields produced as a result of turning of the electrons (reference 5-4). This theory has proven successful in explaining the test observations.

The first EMP tests on systems were carried out by Phillips Laboratory (formerly the Air Force Weapons Laboratory) in 1963. HEMP testing of communication systems did not begin, however, until the late 1960s. The early system tests were performed on elements of the common carrier network, including elements that were intended to support communications for the Safeguard antiballistic missile system. In 1974, the Defense Nuclear Agency (DNA) initiated the Program for EMP Testing. This program included testing of telephone system switches using the Transportable EMP Simulator (TEMPS), continuous wave (cw) field illumination, and direct-drive testing. These tests were followed by the Assessment of Pacific Communications for Hardness to EMP program, which addressed the vulnerability of a complex of facilities at Wahiawa on Oahu and included the use of the TEMPS simulator and a portable cw illumination system.

In response to the threat posed by HEMP, steps were begun toward the establishment of standards for the hardening of systems. In 1982, DNA was assigned responsibility

TABLE I. **Major events.**

Year	Event
1945	TRINITY test; electronic equipment was shielded, reportedly because of Fermi's expectations of electromagnetic signals from a nuclear burst
1952-1953	First British atomic tests; instrumentation failures attributed to "radioflash"
1958	Joint British/U.S. meeting begins discussion of system EMP vulnerability and hardness issues
1962	FISHBOWL high-altitude tests; electromagnetic measurements driven off scale; first indications of the magnitude of the HEMP signal; some system effects noted
1963-1964	Theory explaining early-time HEMP fields developed by Karzas, Latter, and Longmire
1965-1966	Army EMP group formed at the Mobility Equipment and Development Center, Fort Belvoir, VA
1967	Pershing missile assessment and hardening program under cognizance of the Army EMP group
1968	Telephone ESS-1 switch and TD2 microwave transmission system tests performed by Bell Telephone Laboratories
1969-1974	Common carrier network test and analysis program sponsored by Safeguard Communications Agency
1971	All Army nuclear weapon effects activities consolidated under Army Research Laboratories (formerly Harry Diamond Laboratories)
1972	First comprehensive EMP phenomenology handbook published by Phillips Laboratory (formerly Air Force Weapons Laboratory); development of the TEMPS threat-level simulator
1972-1973	U.S. Army Nuclear and Chemical Agency publishes nuclear criteria
1974	Army Electromagnetic Pulse Operations simulator developed
1974–1976	Telephone switch tests using TEMPS, direct-drive, and cw field illumination
1977-1978	Pacific communications systems HEMP testing at Wahiawa, Hawaii; portable cw test system developed
1978	Special joint issue on EMP published in IEEE *Transactions on Antennas and Propagation and Electromagnetic Compatibility*
1982	Assistant to the Secretary of Defense for Atomic Energy designated as focal point for HEMP standardization; responsibility for standardization of HEMP protection of fixed, ground-based facilities delegated to DNA and DISA
1984	Special issue of Journal of Defense Research devoted to EMP
1985	DoD-STD-2169 HEMP environment standard issued
1990	MIL-STD-188-125 HEMP protection standard for fixed, ground-based facilities completed

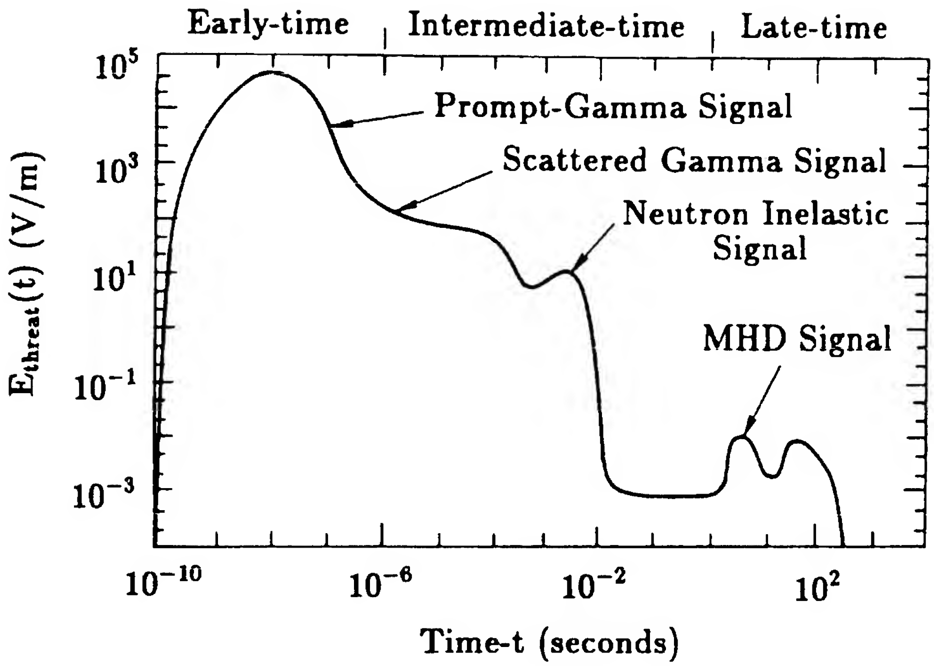
within the DoD for developing a HEMP environment standard. DNA and the Defense Information Systems Agency (DISA) were assigned joint responsibility for developing a HEMP protection standard for application to fixed, ground-based facilities. The HEMP environment standard, DoD-STD-2169, was issued in 1985. A HEMP protection standard, MIL-STD-188-125, was completed in 1990. This handbook is designed to support implementation of the MIL-STD-188-125 protection standard.

5.3 **The HEMP environment.**

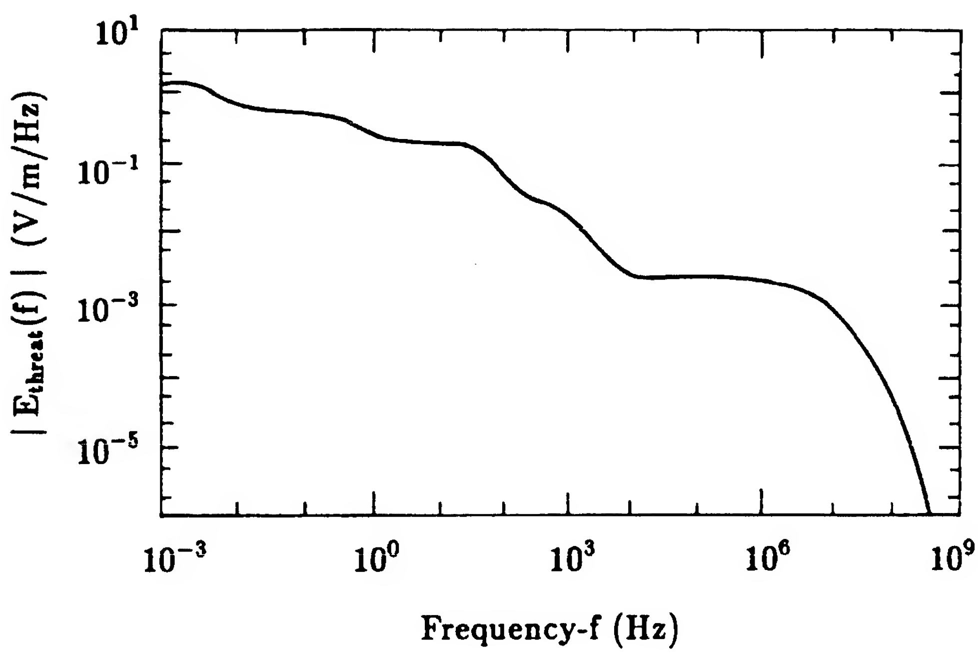
5.3.1 **HEMP generation and characteristics.** Electromagnetic pulse signals are generated by nuclear bursts at any altitude (references 5–3 through 5-6). The signals are driven by the gamma rays which are emitted from the device as the prompt gamma rays or produced as a result of interactions of neutrons in the media outside the device. The nature of the EMP signal depends on factors such as the device yield, burst altitude, and the observer location. For heights of burst above 20 km, locations on or near the earth's surface can be illuminated by an electromagnetic pulse which rises to a peak level of about 50 kV/m within a few nanoseconds and then decays gradually over a period of hundreds of seconds, as illustrated qualitatively in figure 3. This figure illustrates the HEMP environment in both the time and frequency domains. As indicated in the figure, the HEMP environment is understood as encompassing three distinct time regimes. A different field-generation mechanism is dominant in each of the three time regimes, as indicated in table II. The dominant driver of the early-time HEMP signal is the prompt gamma rays from the device. The prompt gamma ray contribution to the HEMP environment is represented by the El component of the standard HEMP environment in DoD-STD-2169. The intermediate-time

TABLE II. **HEMP generation regimes and mechanisms.**

Time Regime	Time Interval	Dominant Driver	Component in DoD-STD-2169
Early-time	$t < 1\ \mu s$	Prompt gamma rays	E1
Intermediate-time	$1\ \mu s \leq t < 1$ s	Scattered and secondary garoma rays	E2
Late-time	$t \geq 1$ s	Magnetohydrodynamic processes	E3



a. **Time history.**



b. **Spectrum.**

FIGURE 3. **Qualitative HEMP time history and spectrum.**

HEMP signal is driven primarily by gamma rays that have scattered as a result of Compton collisions in the atmosphere and secondary gamma rays produced by neutron collisions in the atmosphere. The scattered and secondary gamma ray contribution is represented by the E2 component in the standard environment. The late-time HEMP signal is driven primarily by the magnetohydrodynamic (MHD) processes involving the interaction of the ionized and heated atmosphere with the geomagnetic field. The MHD contribution to the HEMP environment is represented by the E3 component in the standard environment.

5.3.1.1 **Early-time HEMP.** Early-time HEMP (reference 5-5) is that portion of the HEMP waveform that occurs within the first microsecond (figure 3). The early-time HEMP field can rise very rapidly, within a few nanoseconds, to a peak value of about so kV/m. It then falls off with a decay time of a few hundred nanoseconds. Corresponding to the rapid rate of rise, the early-time HEMP environment has significant frequency content extending to hundreds of megahertz and beyond. Because early-time HEMP was the first portion of the waveform to be identified historically and has been seen as posing a potential threat to the widest range of systems, the term HEMP has often been used to refer exclusively to this portion of the overall HEMP waveform.

The early-time HEMP signal is generated as a result of Compton collisions of weapon-produced gamma rays in the atmosphere at altitudes between approximately 20 and 40 km. Above the HEMP source region, the atmosphere is too thin to support an appreciable number of gamma ray collisions. The garoma rays have been largely absorbed by the atmosphere before they can penetrate to lower altitudes. In the source region, Compton recoil electrons having energies of a fraction of an MeV or more are emitted from each gamma ray collision. The process for a single collision is illustrated in figure 4. There are many such collisions in the source region, and the cumulative effect is the initiation of a net, forward-directed flow of Compton recoil electrons. The motion of these electrons in the earth's magnetic field causes them to turn, and the initial part of the turning motion causes an electromagnetic field to radiate in the direction of the incident garoma ray flux. Along any straight path from the burst to an observer located below the source region, the radiated fields add coherently; i.e., the fields from electrons produced at higher altitudes add to the fields produced by electrons at lower altitudes. This is because the HEMP fields and the unscattered prompt garoma rays both propagate along the path at the speed of light. This additive process is illustrated in figure 5.

The maximum level of the HEMP signal produced by this process is limited by the eventual exhaustion of the prompt garoma rays as the pulse moves through the atmosphere and-most importantly-by the buildup of conductivity in the atmosphere as a result of the ionization produced by collisions of the Compton recoil electrons. As a result, the maximum field levels "saturate" at a level of about 50 kV/m. The phenomenon of

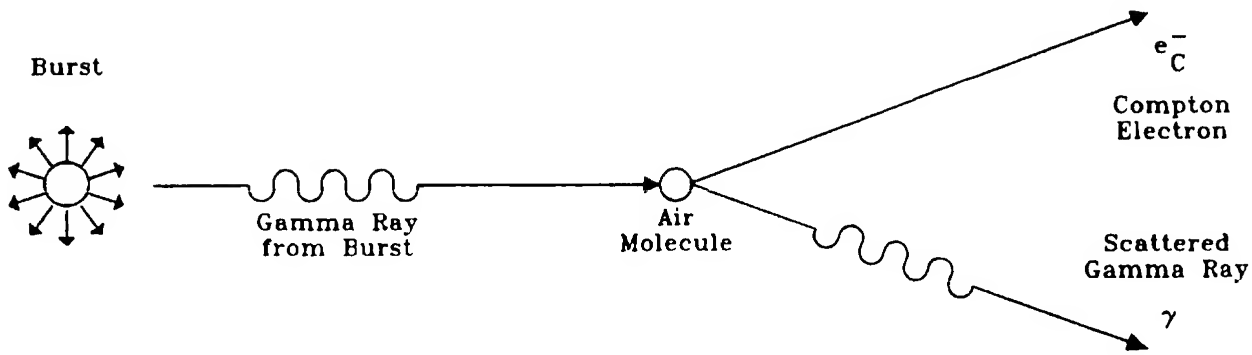


FIGURE 4. **Compton collision process.**

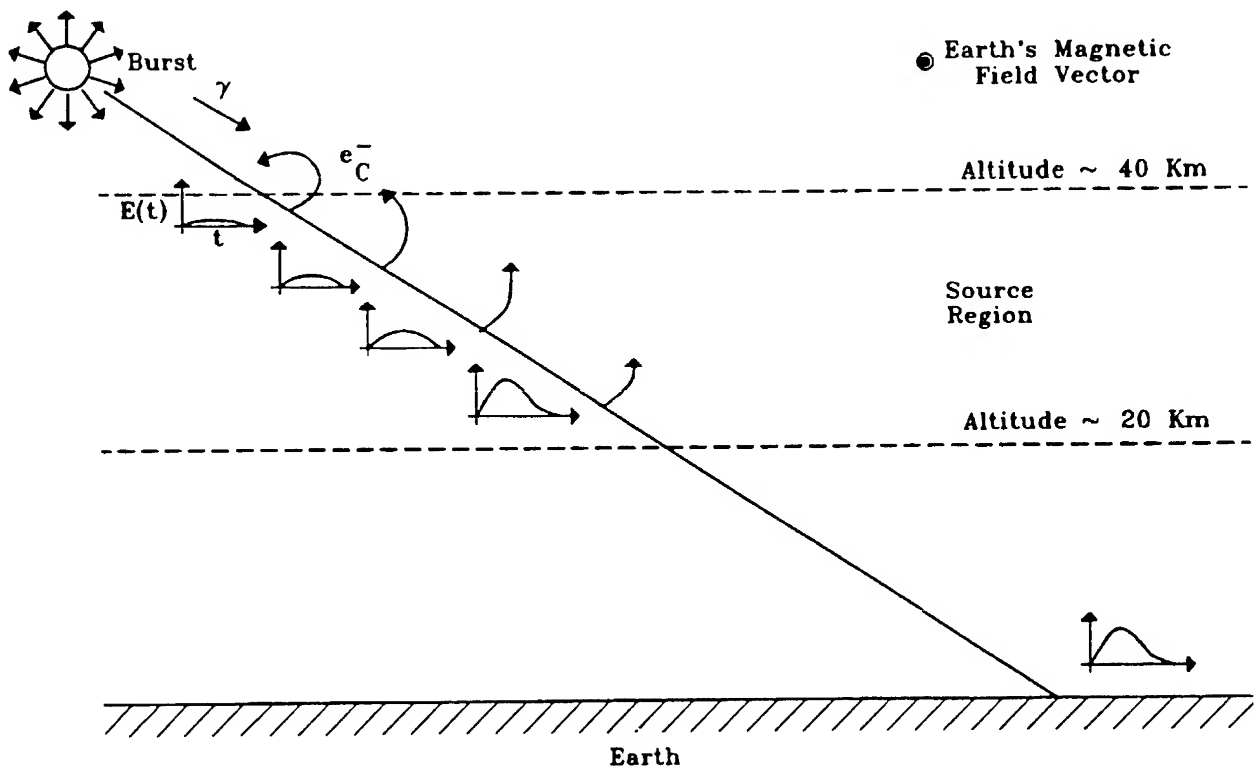


FIGURE 5. **Geometry for the production of early-time HEMP.**

saturation implies similar environments will be produced by a broad range of weapons and makes it practical to define a single, standard HEMP threat.

The early-time HEMP environment illuminates the entire portion of the earth's surface that is visible from the burst, as indicated in figure 2. The HEMP fields arrive as a near-plane wave; i.e., the electric and magnetic fields do not vary appreciably in a plane perpendicular to the direction of propagation, and the magnetic and electric fields are related to each other by the constant free-space impedance. The intensity, time dependence, and polarization of the HEMP fields vary somewhat throughout the illuminated region. The details depend on factors such as the weapon yield, the direction of the burst from the observer, and the direction and intensity of the geomagnetic field in the source region along the line between the observer and burst point. Since the burst point cannot be predicted, however, the same reasonable worst case environment is applicable to all ground-based locations.

5.3.1.2 **Intermediate-time HEMP.** Intermediate-time HEMP occurs between one microsecond and one second after the initial arrival of the pulse. The drivers responsible for producing the dominant component of the intermediate-time HEMP environment (E2) are the scattered and secondary gamma rays. During intermediate times, contributions to the electromagnetic signal reaching an observer come from an expanding volume of the source region, as determined by time-of-flight considerations and attenuation of signals propagating through the time-varying conductivity of the air. The HEMP source region for generation of the intermediate-time HEMP environment is illustrated in figure 6.

The intermediate-time HEMP fields are produced by magnetic-field turning, charge separation, and asymmetries in the source region. However, the various contributions to the fields at an observer location are no longer in phase. Consequently, the field levels are lower than they were in the early-time regime. The peak amplitude of the electric field is on the order of tens of volts per meter (figure 3), and the dominant frequency content lies between 1 Hz and 500 kHz.

Due to the large extent of the effective source region relative to the distance from the source region to the observer, the observer cannot be considered to be in the far field of an effective radiator throughout the entire intermediate-time regime. Accordingly, the incident HEMP environment cannot be considered to be a plane wave throughout this regime. Additional details regarding the generation mechanisms and the complexity of the intermediate-time HEMP environment are presented in reference 5-6.

5.3.1.3 **Late-time HEMP.** Late-time HEMP is the portion of the HEMP environment that begins one second after initial arrival of the HEMP signal and continues for

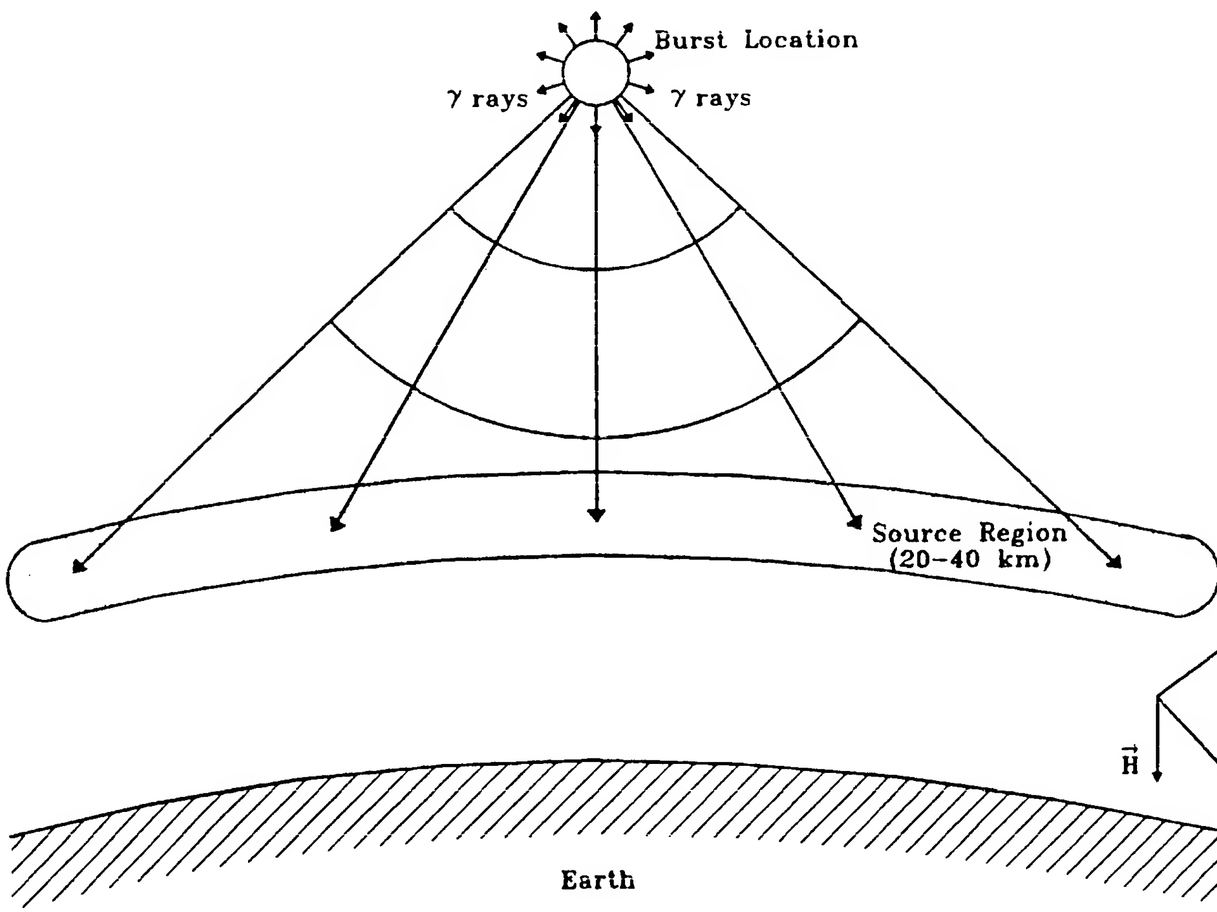


FIGURE 6. **HEMP source region.**

hundreds of seconds. The primary signal generation mechanism in this regime involves the interaction of moving, ionized air masses with the geomagnetic field. Both the generation mechanism and the resulting fields and currents bear resemblances to those of natural magnetic storms. The major differences involve the spatial distributions of the disturbances and the larger field magnitudes and time derivatives involved in the HEMP signal.

Because of the magnetohydrodynamic processes involved in generating the environment, late-time HEMP has been referred to historically as MHD EMP. This component of the HEMP environment is identified as E3 in the standard environment. The theory and modeling of MHD EMP are much less well developed than they are for the earlier components. MHD EMP is currently thought of as comprising three phases: a blast phase (1-15 seconds), a diffusion phase (15-30 seconds), and a heave phase (30 seconds to several minutes).

In the first phase, the motion of the conducting plasma formed by the burst across the geomagnetic field lines gives rise to plasma currents that perturb the geomagnetic field. Points on the earth's surface are shielded for a time from the direct effects of these field perturbations by the conducting layer formed in the atmosphere under the burst as a result of gamma and X-ray energy deposition. Nevertheless, field perturbations do leak around the edges of the conducting layer and do reach the earth's surface. In the next phase, the geomagnetic field perturbations penetrate the conducting layer of the atmosphere by diffusion. In the final phase, the heated and ionized portion of the atmosphere moves slowly upward and further perturbs the existing fields.

The variations of the geomagnetic field that are produced in MHD EMP induce eddy currents in the partially conducting earth. Along with these eddy currents, electric fields with magnitudes determined by the earth's skin resistance are set up in the earth. The blast and diffusion phases produce the strongest electric fields because they produce the strongest temporal and spatial variations of the geomagnetic field. The MHD EMP fields are characterized by low amplitudes, tens of volts per kilometer, large spatial extent, and very low frequencies. The penetration skin depths for this HEMP component can be very large, about one kilometer for sea water and 30 kilometers for the continental land masses.

5.3.2 **HEMP environment specifications.** A standard HEMP environment specification has been established for use throughout the DoD in the hardening of systems for which HEMP hardness is required. This environment specification, referred to here as the DoD standard environment, is defined in DoD-STD-2169, "High-Altitude Electromagnetic Pulse (HEMP) Environment (U)."

According to the hardening strategy adopted in MIL-STD-188-125, system-hardening design and test engineers will not generally need to use the DoD standard environment directly. Design and test specifications in MIL-STD-188-125 are expressed in terms of shielding effectiveness for the HEMP shield and architectural, mechanical, and structural POEs and in terms of coupled quantities for electrical penetrations. These coupled quantities have been calculated "off-line" and are presented in the protection standard. The coupling calculations were performed using the DoD standard environment as an input.

The following brief discussion of the DoD standard environment is included here in order to facilitate an understanding of the intent, derivation, and meaning of the DoD standard environment.

5.3.2.1 **The DoD standard environment.** The DoD standard environment. in DoD-STD-2169 represents the current best judgment of the EMP environment research community regarding an appropriate HEMP criterion. The DoD standard environment was

designed to account for any HEMP environment that an enemy could, at his discretion and at modest cost, impose on a substantial portion of U.S. assets. This threat is mandated for use throughout the DoD for the HEMP hardening of systems and subsystems that have nuclear survivability and hardness requirements.

The DoD standard environment is made up of three components. Each component corresponds to a distinct field generation mechanism and time interval: El for times earlier than one microsecond, E2 from one microsecond to one second, and E3 from one second through hundreds of seconds. The peak fields and fastest rates of change of fields occur during the early-time component. This early-time component is based on the EMP environments calculated for specific weapon designs.

The El does not correspond exactly to any one of the calculated environments. Instead, it has been formulated so as to encompass the peak fields, energy densities, and frequency content of all of the predicted environments. Although it represents an envelope of a number of the environments, it is not excessive in that it does not greatly exceed the environment calculated for a single weapon.

A system designed to tolerate the DoD standard environment can be expected to function acceptably when exposed to any actual HEMP environment.

5.3.2.2 **Earlier HEMP environment criteria.** Other HEMP environment criteria have been proposed for and used in system programs in the past. Most notable of these earlier criteria are the unclassified "double exponential" criterion and the Air Force Nuclear Criteria Group criterion. These earlier criteria are deficient in some important respects (reference 5-7), although the deficiencies do not appear to have been critical in the context of the earlier applications. The older specifications have now been superseded by the DoD standard environment as specified in DoD-STD-2169.

Although superseded by DoD-STD-2169 for formal applications, unclassified double exponential representations of the early-time component of the HEMP environment continue to play a role in informal studies. An early version of the double exponential environment was published by Bell Laboratories (reference 5–8) and, hence, is sometimes referred to as the 'Bell double exponential" environment or waveform. The following is a generalization of the double exponential electric field, *E(t),* waveform:

$$E(t) = E_p k \left(e^{-\beta t} - e^{-\alpha t}\right) \qquad \text{for} \qquad t \geq 0 \tag{3}$$

where

t = Time

E_p = Peak field amplitude

α = Rise constant

β = Decay constant

k = Normalization factor included so that the peak of the waveform will equal E_p

The normalization factor is determined by the values of α and β, according to the following expression:

$$k = \frac{\alpha}{\alpha - \beta} \times \left(\frac{\alpha}{\beta}\right)^{\beta/(\alpha-\beta)} \quad (4)$$

The values of these parameters as presented in several commonly used versions of the double exponential waveform are given in table III.

TABLE III. **Double exponential waveform parameters.**

Parameter	Bell Laboratories (ref. 5-8)	DNA-TR-88-123 (ref. 5-5)	DNA-EMP-1 (ref. 5-9)
E_p	5.0×10^4	5.4×10^4	5.0×10^4
α	4.76×10^8	1.20×10^9	4.76×10^8
β	4.0×10^6	4.3×10^7	3.0×10^7
k	1.050	1.174	1.285

Other sets of parameters have been proposed from time to time for the purpose of more accurately representing the reasonable worst case HEMP environment. However, none of the unclassified sets of parameters adequately represent the DoD standard environment.

The Fourier transform of the double exponential waveform provides a frequency-domain criterion whose amplitude spectrum, $|E(w)|$, is

$$|E(\omega)| = \frac{E_p k(\alpha - \beta)}{\sqrt{(\omega^2 + \alpha^2)(\omega^2 + \beta^2)}} \tag{5}$$

where w is the angular frequency in radians/second.

It is important to recognize that the unclassified double exponential representations are not the criteria against which systems are to be hardened and tested. They do not adequately represent the early-time phase of the HEMP environment, and they do not account at all for the later time phases. The proper use of the unclassified double exponential waveform is for illustrative purposes, preliminary analyses, and sensitivity studies. For actual system applications, it is necessary to relate hardening design specifications and test conclusions to the DoD standard environment, as specified in DoD-STD-2169, or to the coupled quantities as represented in MIL-STD-188-125.

5.3.3 **HEMP compared with lightning.** Lightning, like HEMP and other forms of EMP, involves a brief but intense electromagnetic disturbance in the atmosphere and thus constitutes a potential threat to the operation of electronic systems (reference 5-10). However, there are important differences between lightning and HEMP having to do with geographical coverage, frequency of occurrence, and interaction with systems.

A lightning event is relatively localized. The direct strike affects only one facility or one set of conductors leading to a facility at a time. The electromagnetic fields radiating from a lightning strike also fall off rapidly with distance. Beyond a few hundred meters, the lightning fields are less stressing on systems than are the fields from HEMP. In contrast, the HEMP from a single burst can illuminate broad geographical areas and numerous systems nearly simultaneously. Because of this, protection strategies which depend on switching of communications paths around affected areas may not be viable. In fact, added switches may represent the primary points of vulnerability.

The relative frequencies of occurrence of lightning and HEMP are also an important consideration. Lightning strikes on, or very near to, a given facility are relatively infrequent, and severe direct strikes are very rare. Because of this, and because of the costs of protecting exposed equipment against a direct strike, the strategy adopted in the telecommunications industry is to merely reduce the equipment outage rate to a tolerable level, rather than to prevent outage altogether. In economic terms, protection is added until the marginal costs of the added protection approximate the marginal costs of the damage being prevented. This strategy is not viable for HEMP protection of facilities

because HEMP exposure is inevitable in the event of high-altitude bursts, and multiple exposures of a given facility are likely in any realistic war scenario. Moreover, for critical, time-urgent missions, temporary outages while equipment is being replaced or reinitialized are generally not acceptable.

Lightning strikes can impose peak currents and voltages that are greatly in excess of those that would be imposed by HEMP on equipment located outside a facility. However, this is not necessarily the case for equipment located inside protected facilities. This is because HEMP-induced currents can rise more rapidly than those induced even by severe lightning strikes, and they rise much more rapidly than those induced by nonsevere strikes or fields radiated from lightning strikes. The high frequencies associated with the rapidly rising HEMP-induced currents may determine the stresses which propagate past protective devices or through apertures in systems and reach equipment inside a facility.

Because of the differences in geographical coverage, frequency of occurrence, and system interactions between HEMP and lightning, the hardness or vulnerability of a facility to HEMP cannot be readily inferred from its lightning hardness or vulnerability. Conclusions about HEMP hardness or vulnerability must be established on the basis of direct, HEMP-relatable testing of the facilities of interest.

5.4 **System response to HEMP.** The interaction of an incident HEMP environment produces electrical stresses on and within the system, as indicated in figure 7. These stresses can produce damage or upset events within system circuitry, and the damage or upset events can lead to an aborted mission. HEMP-induced stresses will be discussed in subsection 5.4.1, and the susceptibility of systems to HEMP will be discussed in subsection 5.4.2.

The term damage, as used here, denotes the complete loss of function of a device in a circuit or the degradation of an operating characteristic to a point outside the acceptable range. Upset refers to temporary impairment of system operation not due to burnout or other permanent damage effects. Examples of upsets include introduction of character errors in a digital data stream, erasure of computer-stored information, and opening of circuit breakers. Whether or not the mission is interrupted as a result of an upset or damage depends upon the damage and upset tolerance of the system.

5.4.1 **HEMP-induced stresses.** The interaction of the HEMP environment with a system produces electrical currents and voltages on system cables, individual wires, and conduits, and current and charge densities on conducting surfaces such as shield walls and electronics enclosures. The process of the interaction of HEMP with a facility is often

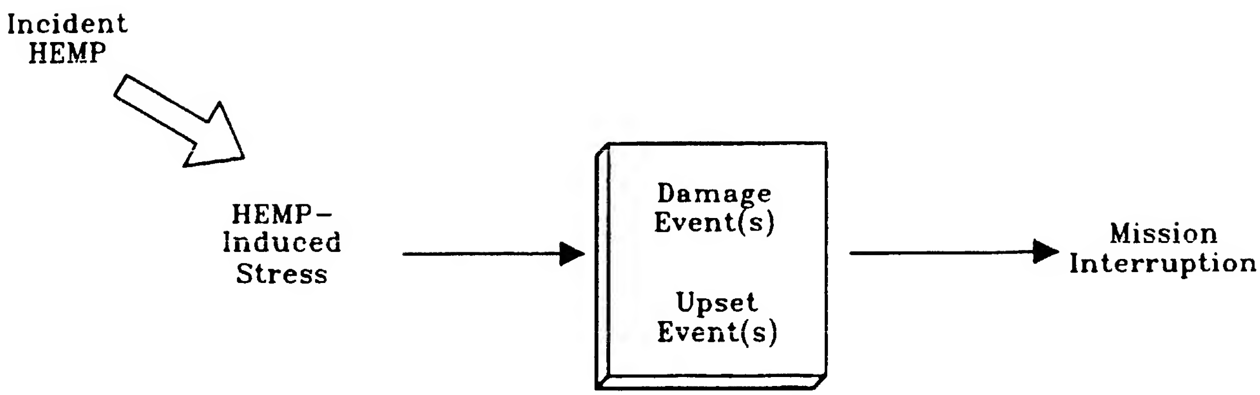


FIGURE 7. **System response.**

referred to as the coupling of HEMP to the facility. The resulting stresses are sometimes referred to as the coupled quantities.

The interaction of HEMP with a system having an overall electromagnetic shield can be thought of as involving a sequence of events. First, the coupling of the incident HEMP fields occurs to the exterior of the system shield and to external connections such as cables, antennas, and pipes. Secondly, HEMP-induced stresses penetrate the system shield. Finally, the stresses are transmitted to equipment located inside the shield. The coupling to the exterior of a system can be analyzed in terms of the following four categories:

a. Long-line coupling – the coupling of HEMP to long lines connected to the shield, including power and communication cables, utility pipes, and metal towers. The coupled quantities of interest are the common mode and differential mode signals and currents on any conduits through which the long lines pass upon entering the facility.

b. Antenna coupling – coupling of HEMP to antennas connected to the shield. Here also, the coupled quantities of interest are the common mode and differential mode signals on signal wires and currents on signal cable shields.

c. Intrasite conductor coupling - coupling of HEMP to short intrasite cables, pipes, waveguides, and other metallic elements. Although these items are not optimized for collection of electromagnetic radiation, they nevertheless act as inadvertent antennas. Coupled quantities of interest are the same as those for other lines.

d. Shield coupling - coupling of HEMP to the exterior of the shield. The coupled quantities of interest are the current and charge densities on the exterior of the shield.

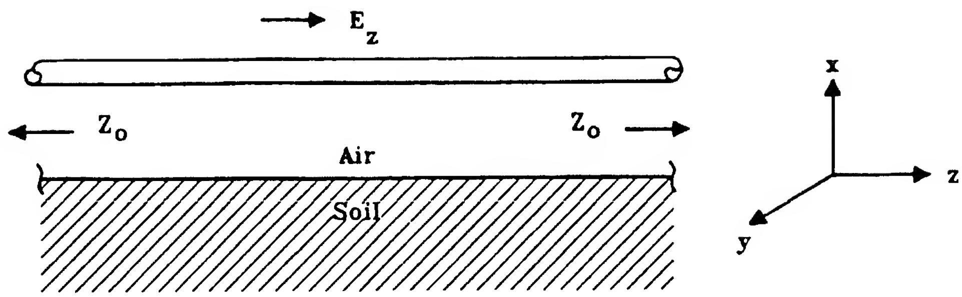
The HEMP coupling in each of these coupling categories depends on a number of variable parameters. These parameters relate to the incident HEMP environment, the system design, and electrical properties of the site. Environment variables include angles of incidence and polarization for the incoming plane wave and the actual field intensity versus time. Responses also depend on the size and shape of the shield, lengths and configurations of electrical conductors outside the shield, and the effective loads. Important site characteristics include the electrical conductivity and dielectric constant of the soil in the vicinity of the system and effects of other nearby structures.

In preparing specifications for hardening and testing of systems, the range of these parameters and their effects on HEMP coupling are taken into account.

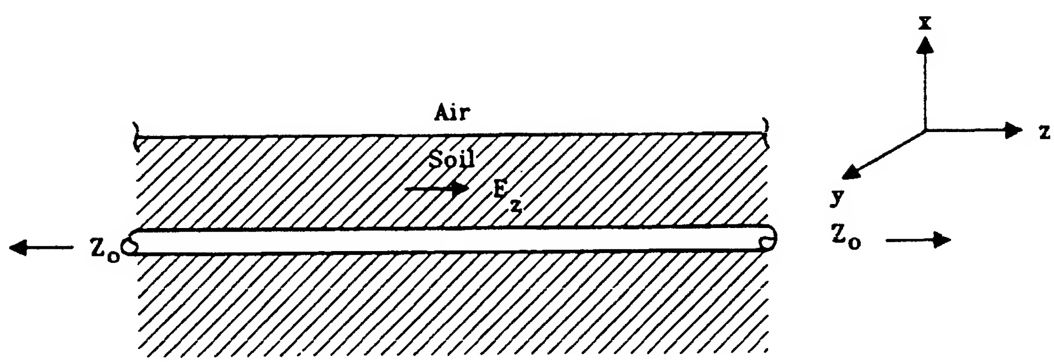
5.4.1.1 **Long-line coupling.** Current will be induced by an incident electromagnetic field on any long conductor if there is a component of the total electric field parallel to the axis of the conductor (reference 5-11). The magnitude of the current induced in the conductor will be proportional to the magnitude of the component of the electric field parallel to the axis of the conductor. Figure 8a illustrates a conductor above the ground, such as is typical of electric power lines and aerial telephone cables. The parallel component of the electric field E_z is illustrated in figure 8a. The conductor and ground behave as a transmission line with characteristic impedance Z_0 between the conductor and ground. Figure 8b illustrates a buried conductor with the component of E_z in the soil and the characteristic impedance Z_0 of the transmission line formed by the conductor and the soil.

The electric field E_z in figures 8a and 8b is the field that would exist along the axis of the conductor if the conductor were not present. For the aerial conductor, E_z is the sum of the incident field and the field reflected from the ground. For the buried conductor, it is the field transmitted into the ground across the air-ground interface. This field may be viewed as the Thevenin-equivalent open-circuit voltage source per unit length that drives the current in the conductor, as illustrated in figure 8c. Along a short element Δz of the conductor, an open-circuit driving voltage E_z x Δz is developed in the absence of the conductor. When the conductor is present, this source is loaded with an impedance of $2Z_0$ which is the sum of the characteristic impedances of the conductor to the right and left of the element.

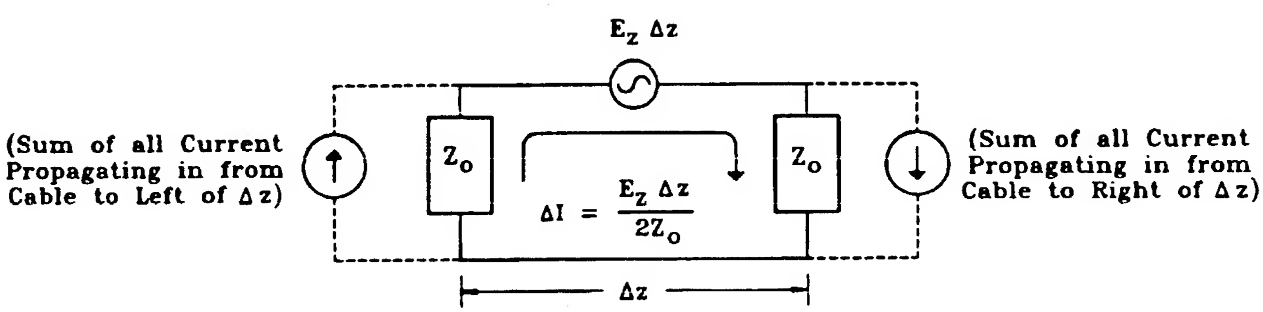
Similar sources exist for all of the elements of the conductor to the right and left of the element under consideration. These sources induce similar current increments in each of the other elements of the line. The net effect is that the total current at any point on the conductor is the sum of all such contributions. The manner in which these other increments arrive and combine at the point of interest depends on the attenuation and



a. Aerial conductor.



b. Buried conductor.



c. Equivalent circuit for determining induced current.

FIGURE 8. **Development of current induced in long lines.**

velocity of propagation along the conductor and on the apparent velocity of propagation, the phase velocity, of the source field E_z along the line.

Reflection at the air-earth interface and attenuation with depth reduces the intensity of E_z at a buried conductor location. Furthermore, the transmission line formed by the buried line and the earth is lossy, so that HEMP-induced currents are attenuated in propagating distances equal to a few skin depths in the soil. Since skin depth is inversely proportional to the square root of frequency, the higher frequency components are more strongly attenuated. Thus, burial of a conductor decreases the peak magnitude of the coupled response and slows the rise time.

For aerial conductors, on the other hand, the attenuation is small and the velocity of propagation along the conductor is nearly the speed of light. The induced current elements may, therefore, propagate for great distances. Furthermore, since they may propagate at nearly the same velocity as the driving field E_z, for HEMP environments incident at small angles with respect to the axis of the conductor, the current elements induced upstream from the point of interest may all arrive at almost the same time. A very large total current may be developed. However, this situation can occur only if the conductor is very long, straight, and uniformly exposed to the HEMP environment.

Reasonable worst case HEMP responses for power and communication lines have been calculated and used to establish design and test specifications in MIL-STD-188-125. These specifications have been extracted from MIL-STD-188-125 and are summarized in table IV.

5.4.1.2 **Antenna coupling.** HEMP coupling to electrically small antennas is simple and reasonably well understood (reference 5-6). A general coupling model for antenna response analysis is shown in figure 9. The antenna itself is modeled as a Norton- or Thevenin-equivalent circuit. The first two-port network can represent an antenna coupling or tuning network or a protection device at the antenna base. A transmission line connects the antenna to the facility, where another matching network or protective device may be present between the barrier and the antenna load impedance. The two-port networks and the transmission line can be modeled using analytical methods or special circuit-theory computer codes. The basic problem is that of determining the elements of the equivalent circuit representing the antenna itself.

Since antennas associated with ground-based facilities can be of almost any type-indeed, many such antennas are “one-of-a-kind” custom designs-the approach that has been taken to their modeling has been to consider a few classes of antennas for detailed study. From the results of these specific studies, inferences are drawn regarding the general

TABLE IV. **Reasonable worst case HEMP response for power and communication lines.**

Class of Electrical POE	Type of Injection	Peak Current - I (A)	Risetime - τ_R (s)	FWHM (s)
Commercial Power Lines (Intersite)				
Short Pulse	Common mode[a]	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Short Pulse	Wire-to-ground[c]	4000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Intermediate Pulse	Common mode[a]	500	$< 1 \times 10^{-6}$	$> 5 \times 10^{-3}$
Intermediate Pulse	Wire-to-ground[c]	500	$< 1 \times 10^{-6}$	$> 5 \times 10^{-3}$
Long Pulse	Common mode[a]	200	< 0.5	> 100
Long Pulse	Wire-to-ground[c]	200	< 0.5	> 100
Other Power Lines (Intrasite)				
Short Pulse	Common mode[a]	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Short Pulse	Wire-to-ground[c]	4000	[b]$< 1 \times 10^{-6}$	5×10^{-7}-5.5×10^{-7}
Audio/Data Lines (Intersite)				
Short Pulse	Common mode[a]	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Short Pulse	Wire-to-ground[c]	[d] $8000/\sqrt{N}$ or 500	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Intermediate Pulse	Common mode[a]	500	$< 1 \times 10^{-6}$	$> 5 \times 10^{-3}$
Intermediate Pulse	Wire-to-ground[c]	500	$< 1 \times 10^{-6}$	$> 5 \times 10^{-3}$
Long Pulse	Common mode[a]	200	< 0.5	> 100
Long Pulse	Wire-to-ground[c]	200	< 0.5	> 100
Control/Signal Lines (Intrasite)				
Short Pulse	Common mode[a]	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Short Pulse	Wire-to-ground[c]	[d] $8000/\sqrt{N}$ or 500	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Conduit Shields				
Buried[e]	Conduit-to-ground[f]	1000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Nonburied	Conduit-to-ground[f]	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}

[a]For a common mode ted, all penetrating conductors in the cable are simultaneously driven with respect to ground, where ground is a point on the facility HEMP shield in the vicinity of the POE protective device. Common mode tests are required for verification, but they are not required for acceptance.

[b] $\tau_R \le 1 \times 10^{-8}$ s is a design objective. The minimum requirement is $\tau_R < 5 \times 10^{-8}$ s.

[c]For a wire-to-ground test, each penetrating conductor in the cable is driven with respect to ground, where ground is a point on the facility HEMP shield in the vicinity of the POE protective device.

[d]Whichever is larger. N is the number of penetrating conductors in the cable.

[e]A conduit is considered buried when it connects two protected volumes and less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill.

[f]For a conduit-to-ground test, maximum feasible length of the conduit is driven with respect to ground, where ground is a point on the facility HEMP shield in the vicinity of the conduit penetration.

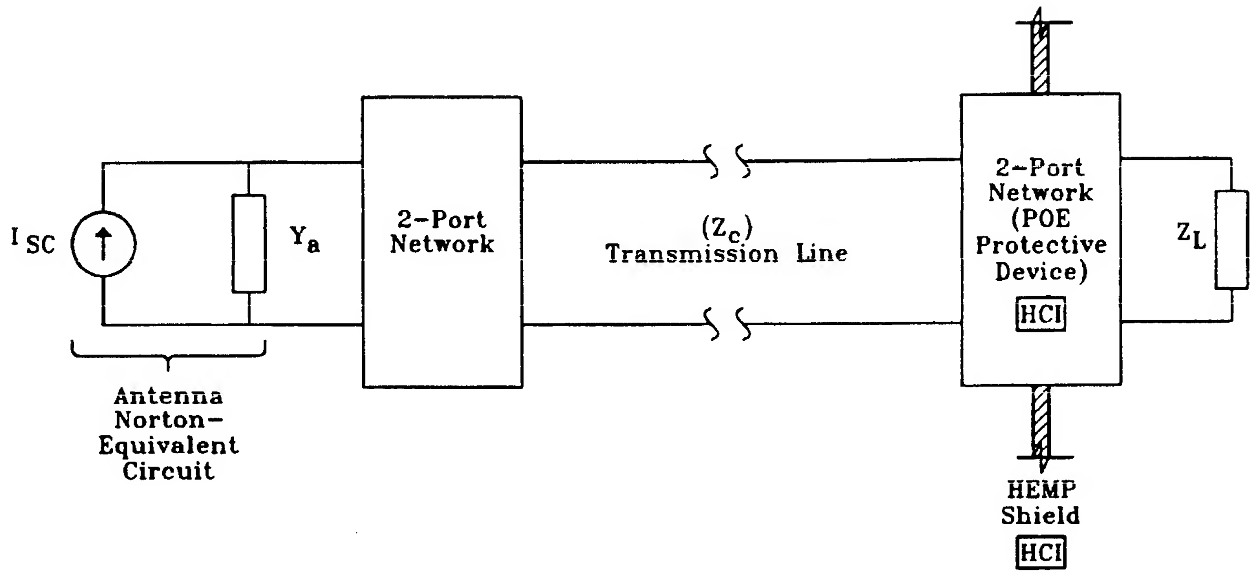


FIGURE 9. **Coupling model for antenna response.**

response characteristics for purpose of standards development. Some of the antenna types which have been modeled include wire antennas in free space, horizontal wire antennas over ground, loaded vertical antennas, and driven and parasitic multi-element array antennas.

The general procedure followed in analyzing the response of an antenna involves two steps:

a. Determine the short-circuit current induced at the antenna terminals by an incident HEMP-like plane wave; this determines the Norton current source.

b. Evaluate the input admittance seen by a source applied to the antenna terminals; this determines the Norton admittance.

In general, it is found that, except for a long wire antenna, the short-circuit current has a damped, quasi-sinusoidal waveform whose center frequency is that of the fundamental resonant frequency of the antenna structure and whose damping rate is related to the bandwidth of the fundamental resonance. The peak amplitude of the current decreases as the fundamental resonant frequency increases, as a consequence of the decreasing amplitude of the HEMP spectrum with increasing frequency. This tendency is offset somewhat by the antenna gain at resonance, which can increase with increasing resonant frequency.

The response of a long wire antenna is more complicated. The induced current is periodic at the fundamental resonant frequency of the antenna, but the waveform is no longer sinusoidal. Rather, each half-cycle of the induced current tends to resemble the incident HEMP waveform in shape. This response results from the fact that several of the antenna resonant frequencies lie in the range where the incident spectrum is nearly flat. The division between long and other antennas occurs where the fundamental resonant frequency is around 5 MHz; that is, long antennas have fundamental resonances below 5 MHz.

Reasonable worst case HEMP responses for antennas that might be installed at ground-based C^4I sites have been estimated for the purpose of establishing the pulsed current injection test specifications in MIL-STD-188-125. The antenna test specifications are presented in table V. In this table, the antennas are classified in terms of effective frequency, f, where f in megahertz is equal to 150 divided by the largest dimension of the antenna in meters.[1]

When a small antenna is mounted on a tall tower, the HEMP-induced currents on the tower will cross-couple into the antenna response function. To account for this interaction, the RF antenna line should also be injected with a short double exponential pulse of 500 A peak amplitude if the tower height exceeds 25 m (82 ft).

5.4.1.3 **Intrasite conductor coupling.** HEMP coupling calculations for short cables, conduits, and pipes generally employ the same basic aerial and buried transmission line models that have been described for long-line geometries. Rather than assuming the conductor is semi-infinite in extent, however, actual length is a parameter of the model. Reasonably faithful representations of the as-designed or as-installed physical configuration and the effective terminating impedances are also required to obtain accurate predictions. Responses may be unipolar or oscillatory depending upon these variables. The peak response current values increase with increasing conductor length until the long-line transients are reached.

MIL-STD-188-125, however, establishes the same short pulse design and test specifications for both intrasite and intersite conductors. This has been done so that conductor length and terminations do not become hardness critical parameters. The intermediate and long pulse requirements are not applied in the case of intrasite conductors.

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[1]The equation in MIL-STD-188-125 for calculating the antenna effective frequency is in error and is being corrected. The correct equation is $f = 150/L$ MHz, where L is the largest antenna dimension in meters.

TABLE V. **Reasonable worst case HEMP response for antennas.**

a. Double exponential waveforms

Class of Electrical POE	Type of Injection	Peak Current - $\hat{I}$ (A)	Risetime - τ_R (s)	FWHM (s)
RF antenna Lines— Signal Conductors [a]$f < 2$ MHz	Wireto-shield	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
RF Antenna Lines— Shield				
Buried[c]	Shield-to-ground[d]	1000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}
Nonburied	Shield-to-ground[d]	8000	[b]$< 1 \times 10^{-8}$	5×10^{-7}-5.5×10^{-7}

b. Damped sinusoidal waveforms.

Class of Electrical POE	Type of Injection	Peak Current - $\hat{I}$ (A)	Center Frequency - f_c (MHz)	Decay Factor - Q (Dimensionless)
RF Antenna Lines-Signal Conductor				
[a]2 MHz $< f < 30$ MHz	Wire-to-shield	[e]2500	[e]2 ± 10%	[e]10±3
[a]30 MHz $< f < 200$ MHz	Wire-to-shield	[e]900	[e]30± 10%	[e]10±3
[a]200 MHz $< f$	Wire-to-shield	[e]250	[e]200± 10%	[e]10±3

[a] $f = 150/L$ MHz, where L is the largest dimension of the associated antenna in meters. When $f < 2$ MHz, a double exponential pulse is required. When $f > 2$ MHz, a damped sinusoidal waveform is specified.

[b] $\tau_R \leq 1 \times 10^{-8}$ s is a design objective. The minimum requirement is $\tau_R < 5 \times 10^{-8}$ s.

[c] An antenna shield is considered buried when it terminates at a buried antenna and less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill.

[d] For a shield-to-ground test, maximum feasible length of the antenna line shield is driven with respect to ground, where ground is a point on the *facility* HEMP shield in the vicinity of the POE protective device.

[e] The damped sinusoidal waveform is a design objective. The minimum requirement is to inject the current output from a PCI source which delivers the following current pulse $[I(t)]$ with an unspecific waveform into a 50 Ω calibration load:

a. $$\int_0^T I(t)\,dt \geq \frac{0.3\hat{I}}{f_c}$$

b. $$|I(t)| \leq K_{DS}\,\hat{I}e^{-\frac{\pi f_c t}{10}} \quad \text{for all } t > T$$

where t is time in seconds, $\hat{I}$ is the prescribed peak current in amperes, f_c is the prescribed center frequency, K_{DS} is a scaling constant, and T is the time of the first zero crossing or $1/f_c$ whichever occurs earlier.

5.4.1.4 **Shield coupling.** HEMP fields couple to the exterior of HEMP shields and can penetrate through imperfections in the shields. The imperfections in any practical shield, aside from the points of penetration of long lines and antenna cables, include the finite thickness and conductivity of the shield materials; recognized apertures in the shield associated with ventilation ducts, and imperfectly sealed personnel access doors and equipment access hatches; and unrecognized apertures in the shield due to improper welding of shield panels, improper installation of penetrating conductor protection, and breaks in the continuity of shield that develop over time as a result of corrosion or mechanical forces. In practical applications, apertures are the dominant imperfections in an electromagnetic shield, after the penetrations of the shield by conductors which extend outside the shield.

The fields and associated current and charge densities coupled to the exterior of a shield are the result of local coupling of incident fields and the result of coupling to the entire configuration of facility, antennas, and long lines. Long-line and antenna-coupled currents produce exterior field concentrations near points of connection to the shield.

The effectiveness of the facility HEMP shield is highly dependent upon the proper treatment of penetrating long-line and antenna cables and on often unrecognized apertures in the shields. Consequently, quantitative estimates of facility shielding effectiveness should be determined by testing. A detailed discussion of test methods and procedures for quantifying shielding effectiveness are presented in section 16 of this handbook.

5.4.1.5 **Interior stresses.** The electrical stresses imposed on equipment inside a facility can be thought of as the sum of four contributions.

5.4.1.5.1 **Long-line contributions.** Each long-line contribution to the stress at a point inside the facility can be represented as the exterior long-line stress times the effective transfer function between the POE of the line into the shielded volume and the point of interest. The effective transfer function should be defined to account for the operation of the protective circuitry at the point-of-entry and the transmission of the stress from just inside the shield to the point of interest. If only linear protection such as a passive filter is provided, then the effective transfer function is a true transfer function which can be determined by low-level testing. If nonlinear protection is included, then the effective transfer function needs to be determined by high-level pulse testing. The total stress at any point inside the facility due to HEMP coupling to long lines may receive significant contributions from more than one long-line POE.

5.4.1.5.2 **Antenna contributions.** Each antenna contribution to the stress at a point inside the facility can be represented as the stress induced by HEMP on the antenna just outside the POE times the effective transfer function, as defined above, between the POE

and the point of interest. The total stress at any point inside the facility due to HEMP coupling to antennas may include significant contributions from more than one antenna POE.

5.4.1.5.3 **Intrasite line contributions.** Intrasite line coupling contributions to the response at an interior observation point can be represented with the same transfer function approach described above. An upper bound is obtained when the PCI test specification is used as the exterior stress. Again, more than one of these POEs can contribute to the stress at an interior location.

5.4.1.5.4 **Shield leakage contribution.** The contribution of shield leakage fields to the stresses at a point inside the facility can be represented as the incident field times an effective transfer function through the shield and to the point of interest. The transfer function, which may be nonlinear, would account for HEMP coupling to the shield, leakage of fields through shield imperfections and apertures, coupling of leakage fields to the conductors inside the facility, and transmission of the resulting signal to the point of interest. The shield leakage transfer function is a function of the angle of incidence and polarization of the incident field. When the shield leakage transfer function is used to relate the level of an internal field to the level of the corresponding incident field, then the inverse of the transfer function is what is referred to as the shielding effectiveness. If the shield leakage transfer function value is sufficiently low or equivalently if the shielding effectiveness is sufficiently high, then the shield leakage contribution can be ignored in estimating interior stresses.

When the HEMP barrier complies with effectiveness requirements of MIL-STD-188-125, the high-frequency shield leakage will be small. In the lower portion of the E2 spectrum and in the E3 regime, however, the shield becomes essentially transparent. The effects of these low-frequency fields on operation of mission-critical systems in the protected volume are not presently well known. Additional information is becoming available as this area of HEMP technology matures, and technical interchange with the DoD and service centers of HEMP expertise for the purpose of obtaining updated results is encouraged.

5.4.2 **System susceptibility.** A broad variety of modern electronic systems has been tested in HEMP environment simulators and by means of direct drive techniques that induce electrical stresses similar to those that could be imposed by HEMP. Malfunctions resulting from circuit upset or damage have been observed in a significant proportion of the systems tested. Based on this evidence, it is clear that modern electronic systems are, in general, susceptible to malfunction upon exposure to HEMP.

Reliable conclusions about the nature and degree of susceptibility of a specific system or facility cannot be drawn in the absence of a detailed test and evaluation performed on that system. However, even with excessively large investments in test and evaluation, one cannot be confident that all of the important HEMP vulnerabilities have been identified, unless the electromagnetic topology of the system is carefully controlled. If the electromagnetic topology of the system is not adequately controlled, then the number and the complexity of the paths by which electromagnetic energy might couple into the facility will render thorough testing impractical. For facilities of uncontrolled design, even if no vulnerabilities are predicted and none are observed during testing, the strongest conclusion that can be drawn is that the facility may be hardened to HEMP effects. The controls on facility topology that are necessary in order to render the facility fully testable, and thus to allow stronger conclusions to be drawn, are described in section 6 of this handbook.

5.5 **References.**

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6. HEMP HARDENING AND THE LOW-RISK APPROACH

6.1 **Basic principles.**

6.1.1 **System susceptibility and the need for hardening.** As noted in section 5, modern electronic systems are in general susceptible to malfunction upon exposure to the HEMP environment. Moreover, it is not possible to establish with confidence that a specific system is hardened to HEMP unless that system has been designed in such a way as to make thorough hardness verification testing possible. Possible vulnerabilities and lingering uncertainty are viewed as unacceptable for critical, time-urgent C^4I systems. Therefore, these systems must be hardened against HEMP, and they must be hardened in such a way that their hardness can be both verified by testing and maintained throughout the operational lives of the systems.

6.1.2 **Hardening strategy.** Critical, time-urgent C^4I systems often rely on equipment distributed among a number of different sites, and thus they extend beyond the confines of any one facility. A complete C^4I system might encompass equipment at ground-based facilities, equipment on airborne or space platforms, and communication links between these facilities and platforms. A ground-based facility could support any of a number of functions within the larger system. It could serve as a network subscriber site, an information collection and processing center, a command center, a switching center, a transmitting and receiving station, or a relay station. While a single system can encompass equipment located at several facilities, it is also true that a single facility can support more than one system. Equipment essential to the operation of several systems might be housed within a single facility.

In order to simplify the HEMP hardening problem in light of the above complications, the hardening strategy presupposed in MIL-STD-188-125 (reference 6-1) is to separately harden individual facilities, platforms, and interconnecting communication links. The intention behind the HEMP hardening of any of these system elements is to provide adequate protection for all equipment required to support the mission-essential functions of the facility, platform, or link. Thus, hardening a facility consists of providing HEMP protection for the mission-essential equipment, and hence for the mission-essential functions, associated with the facility. As used in MIL-STD-188-125, the term "facility" refers to the collection of equipment, buildings and structures that support critical, time-urgent C^4I systems and that are located at a single site.

While each facility is to be independently hardened, the criteria for hardening effectiveness must reflect the larger C^4I system requirements. These requirements form the

starting point for the development of pass/fail criteria for functional hardness verification. In the context of this strategy, MIL-STD-188-125 and this handbook are concerned only with the HEMP hardening of ground-based facilities.

6.1.3 **Facility hardening program goal and objectives.** The overall goal of a facility HEMP hardening program is to ensure that the mission-essential functions performed in the facility are adequately protected against the effect of HEMP throughout the operational life of the facility. A HEMP-hardened facility is one in which the mission-essential functions of the facility will not be disrupted or unacceptably degraded as a result of exposure to HEMP.

Successful HEMP hardening depends upon the development of an effective hardening design and the careful implementation of the design during construction. To ensure that hardness has been achieved, it is necessary to verify facility hardness by means of testing. Moreover, retention of hardness throughout the operational life of a facility requires attention to hardness maintenance. Thus, a comprehensive facility HEMP hardening program involves meeting the following four objectives:

a. Design – development of an effective HEMP hardening design

b. Construction – careful construction of the facility in accordance with the hardening design

c. Verification – initial and life-cycle hardness verification.

d. Hardness maintenance/hardness surveillance – development and implementation of an effective HM/HS program

The four objectives are not independent. The ability to construct, test, and maintain the HEMP hardness of a facility must be accounted for in the hardening design.

In the remainder of this section, the general principles of HEMP hardening are reviewed. Then, the concept of low-risk hardening is introduced and the low-risk approach—as it has been formulated in MIL-STD-188-125 for application to fixed, ground-based C⁴I facilities-is explained. The hardening approach and guidance for application to transportable systems will be described in volume II of this handbook.

6.2 **HEMP hardening.**

6.2.1 **General principles of hardening.** HEMP hardening can be thought of as consisting of some combination of stress reduction and equipment strength enhancement.

Stress reduction involves reducing the levels of HEMP-induced stress that could reach mission-essential and potentially susceptible equipment to levels that can be tolerated (or to levels above which the MEE can be strengthened). Equipment strength enhancement involves increasing the strength of MEE so that it will be able to tolerate exposure to higher levels of stress.

Stress reduction is generally achieved by imposing an electromagnetic barrier or barriers between the incident threat environment and the potentially susceptible equipment (reference 6-2). Strength enhancement is achieved by establishing a final electromagnetic barrier at the level of the equipment enclosure, by circuit design or selection of electronic components, and by software changes. If the strength of the MEE exceeds the reasonable worst case HEMP-induced stress levels for each piece of mission-essential equipment, then the system can be said to be hardened against HEMP.

The MIL-STD-188-125 hardening approach places primary reliance on a single-layer electromagnetic barrier to reduce or control the levels of stress allowed to reach mission-essential equipment, and it places minimal reliance on equipment strength enhancement. In view of the importance of the HEMP barrier to HEMP hardening in general, and to the approach mandated by MIL-STD-188-125 in particular, the concept of the HEMP barrier will be presented before continuing with the discussion of HEMP hardening.

6.2.2 **The HEMP barrier.** The purpose of a HEMP barrier is to limit the levels of HEMP-induced stress allowed to enter the protected volume enclosed within the barrier. A HEMP barrier is made up of:

a. An electromagnetic shield—a shielded enclosure with penetrations only where necessary to support the operation of equipment and the activities of personnel in the protected volume

b. Protective treatments applied to each POE in the shield

In practical C⁴I facilities, POEs in the shield will generally be necessary in order to provide for the transfer of information into and out of the protected volume; electrical power; heating, ventilation, and air-conditioning; the entry and exit of personnel and equipment; and access to equipment for maintenance. In providing for these functions, penetrations must be made in the shield walls and, in some cases, electrical conductors must be allowed to pass through the openings.

All penetrations in an electromagnetic shield constitute potential "points-of-entry," through which electromagnetic energy can be transmitted from outside the shield into the

protected volume. Shield POEs through which electrical conductors do not pass are termed apertures. These include intentional apertures for personnel entry and fluid flow through the shield and inadvertent apertures such as holes or cracks. POEs through which electrical conductors do pass are termed conductive POEs or simply penetrating conductors.

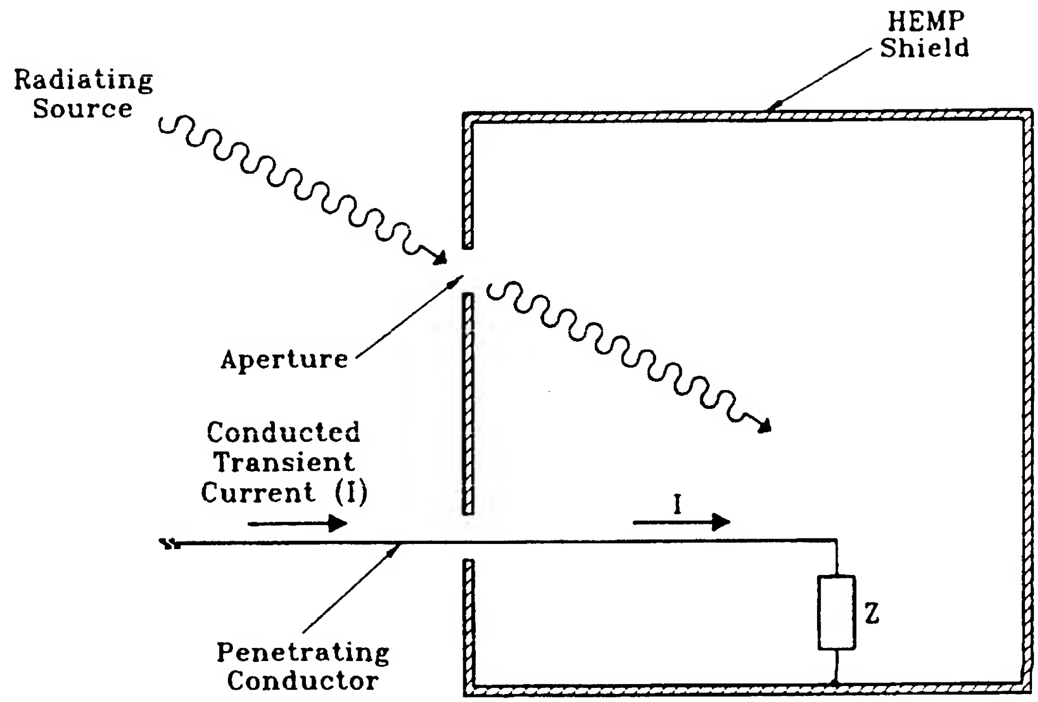
If left untreated, POEs would severely undermine the effectiveness of a HEMP barrier as indicated in figure 10a. In this figure, both radiated and conducted transients are allowed to enter through untreated POEs in the shield. In an effective HEMP barrier, each POE must be treated so as to reduce or control the levels of stress allowed to enter the protected volume (figure 10b). In designing a HEMP barrier, POEs in the barrier should be eliminated wherever possible. Then hardening treatments must be designed for each of the remaining POEs. Typical treatments on penetrating conductors of power and signal lines employ combinations of surge arresters and filters. Aperture POEs are protected with waveguides-below-cutoff and with RFI-gasketed metal covers and doors.

The shield and aperture treatments of a HEMP barrier are generally intended to provide sufficient shielding effectiveness so that the stresses produced by HEMP inside the protective volume as a result of field leakage through the shield and apertures are negligible. These stresses are negligible if they are much lower than the stresses allowed to enter through the penetrating conductor POEs or the stresses routinely experienced and tolerated by equipment inside the barrier during normal system operation. A high-quality shield having a nominal shielding effectiveness of 100 dB[2] or more will be generally sufficient for this purpose. A steel or copper shield, as required by MIL-STD-188-125, would provide greater shielding effectiveness than is necessary in most applications, provided that the POEs in the shield are effectively treated.

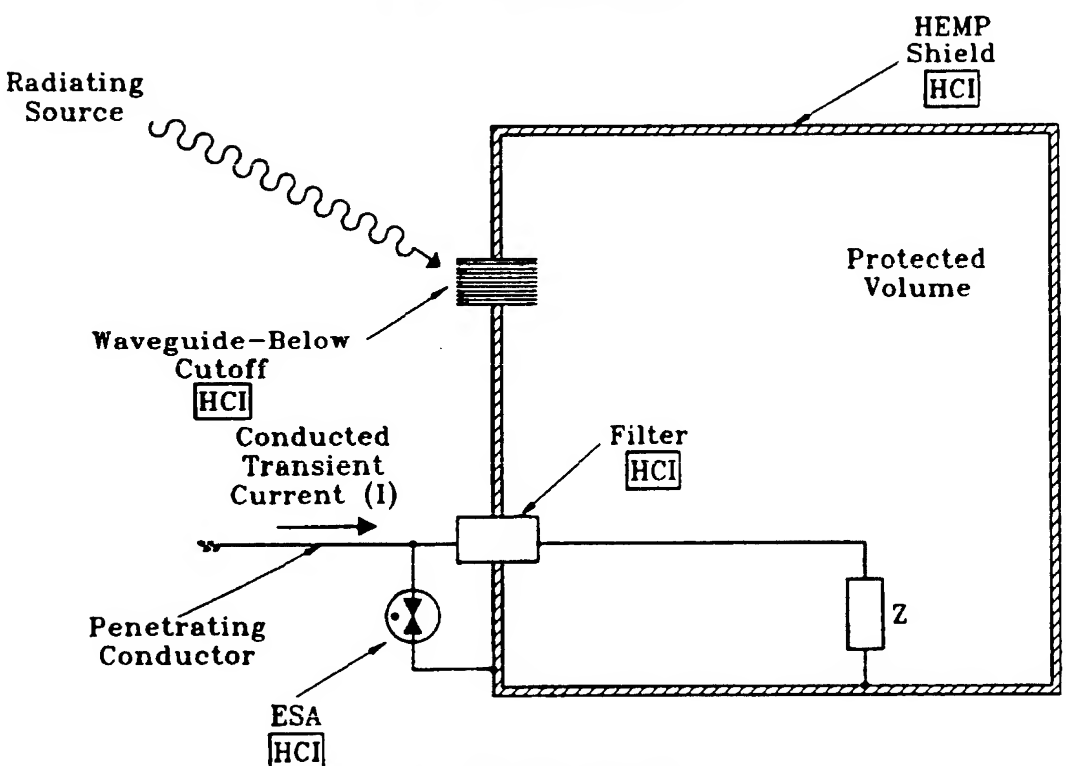
The conducting penetration POE treatments must allow required electromagnetic power and information signals to pass through the barrier while preventing HEMP-induced stresses which might lead to system malfunction from entering the protected volume. Guidance and information to support the detailed design of conducting penetration POE treatments are provided in section 12.

6.2.3 **Generalized hardening approach.** Any hardening approach can be thought of as involving the use of single-layer or nested barriers to establish a number of different zones of protection within a system (figure 11). Each zone in this "zonal hardening"

[2]A complete definition of shielding effectiveness performance requires attenuation as a function of frequency, when measured by a specified procedure. The 'nominal" shielding effectiveness is the performance over some mid-frequency range. When used in this handbook, nominal shielding effectiveness implies the electric and plane wave performance over the frequency band from 10 to 100 MHz measured by the procedure of MIL-STD-188-125.



a. **Ineffective barrier.**



b. **Effective barrier.**

FIGURE 10. **Effective and ineffective HEMP barriers.**

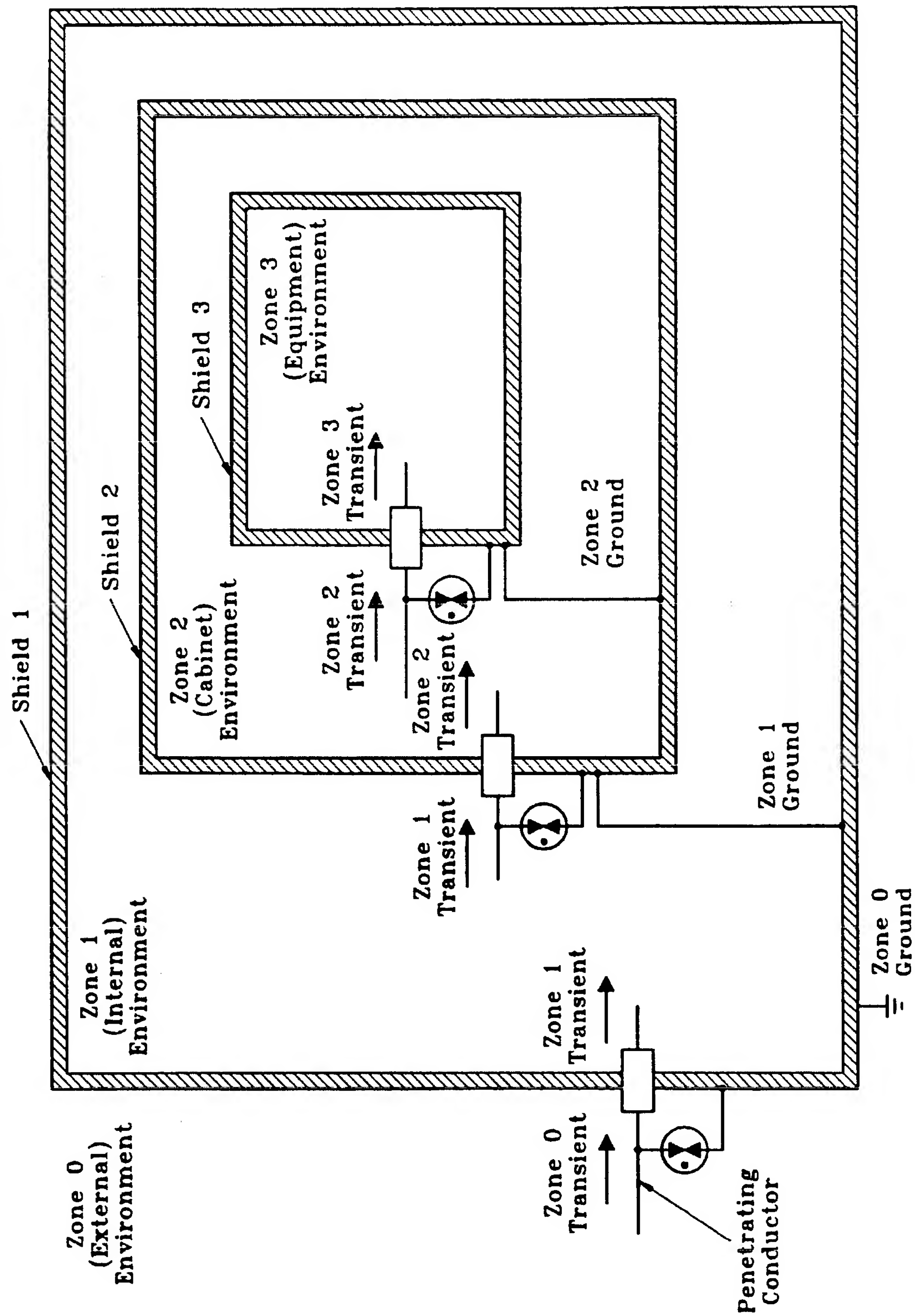


FIGURE 11. Zonal or allocated hardening.

FIGURE 11. Zonal or allocated hardening.

approach could have its own stress control specification. In figure 11, zone 0 corresponds to the volume outside of the outermost HEMP barrier. No stress control specification would be imposed on zone 0; the stresses in this zone would be limited only by the threat environment and worst case coupling to external conductors. Protective elements would be located in zone 0 for the purpose of controlling the stresses allowed to enter zone 1. Zone 1 corresponds to the region inside the first barrier, bounded by shield 1 in figure 11. Zone 2 corresponds to the region inside the second of the nested barriers. The zone 2 environment should be "quieter" than the environment in zone 1, inasmuch as the second barrier should act to reduce the stress levels in zone 2 below those in zone 1.

The zonal hardening approach has also been referred to as the allocated or distributed hardening approach because the total requirement for stress control is allocated to or distributed among the successive barriers. As illustrated in figure 11, this approach allocates some of the HEMP protection for the MEE to the facility-level barrier, some to a second barrier at the room or cabinet level, and some to a third barrier at the equipment level.

In the zonal or allocated hardening approach, for each zone there is a corresponding maximum allowable level of stress. The equipment to be placed in the various zones would be required to have sufficient hardness to be able to tolerate stresses up to the allowable levels for the corresponding zone. Generally, the equipment would be hardened to the allowable levels plus some margin to account for uncertainties and hardness degradation with time.

6.3 The low-risk hardening approach.

6.3.1 **Fundamentals of low-risk hardening.** A low-risk HEMP hardening approach is one in which the likelihood or risk of mission-essential equipment being upset or damaged as a result of exposure to HEMP is low. Low-risk hardening is achieved by following a hardening approach that depends upon a limited number of highly reliable hardening elements. It lends itself to thorough hardness verification and can be readily maintained. In order to achieve low-risk hardening, a hardening design must minimize the following:

a. Reliance on analytic predictions of HEMP interactions and system responses and dependence upon unverifiable assumptions about equipment susceptibility

b. The number of hardness critical items that are introduced into the system and must be controlled in order to ensure hardness

Analytic predictions of HEMP interactions with systems have been found to be subject to large errors and uncertainties. Similarly, equipment susceptibility to damage or

upset due to electrical overstress is often not well understood or controlled and cannot be established with high confidence without prohibitive investments in testing. The number of HCIs in a system must be controlled since it affects both the reliability and the maintainability of the HEMP protection.

Low-risk hardening can most easily be achieved and maintained by placing primary emphasis on controlling the stresses that could reach the MEE in a facility. This is because HEMP-induced stresses can be controlled using a relatively small number of HCIs-a smaller number than would be required in order to control equipment strength or in order to control both stress and strength. The total number of HCIs and the reliance of the hardening design on analytic predictions and unverified assumptions are minimized by enclosing all of the MEE that can be made to operate inside an electromagnetic barrier inside a single, overall HEMP barrier (or a small number of barriers when equipments are physically separated). Special protective measures must be taken for the few items of MEE, such as transmit and receive antennas, that cannot be made to operate within a HEMP barrier and for the relatively few items of MEE which cannot tolerate the residual stresses inside the protected volume.

No hardening design, not even a low-risk design, is risk free. Sources of risk are encountered at each stage in the hardening design and implementation process. Because of the imperfections in any real hardening program, there is a significant risk that residual vulnerabilities will remain in systems that have ostensibly been hardened and have passed all of the required acceptance tests. In order to achieve low-risk hardening, all of the significant remaining vulnerabilities with unacceptable consequences and nonzero likelihood of occurrence must be identified and removed. The only reliable means by which these vulnerabilities can be identified is through thorough hardness verification testing. In verification tests, threat-like environments or threat-induced stresses are applied to the system, and the functional response, data traffic, and memory contents of the system are monitored. Additional details on verification test requirements, as specified in MIL-STD-188-125, are presented in section 16 of this handbook (also see reference 6-3).

No HEMP environment simulator is capable of exposing typical ground-based facilities to the full threat environment and, in any case, routine testing with such a simulator would not be practical. Thus, verification testing can only be performed by directly exciting the facility with up to the expected reasonable worst case HEMP-induced stresses (or to bounds on these stresses). However, for direct excitation or pulsed current injection testing to be feasible, there must be no more than a testable number of system excitation points. It must also be possible to establish practical bounds on the HEMP-induced stresses at these points. This requires that the system be enclosed by an electromagnetic barrier or a small number of independent barriers having a testable number of POEs. The

POEs must also be accessible for excitation of the POEs and for the measurement of the coupled stresses and internal responses.

The hardness of a facility is subject to degradation in the course of time as a result of environmental exposure including corrosion and effects of electrical overstress due to lightning, wear on hardness critical items, life-cycle degradation of system components, the introduction of more sensitive equipment into the facility, and the inadvertent introduction of flaws into the HEMP barrier during the installation of new equipment and facility modifications. As a result, a low-risk hardening program must also provide for the identification of unacceptable hardness degradations and for corrective maintenance when needed. To identify unacceptable hardness degradations, it will be necessary to perform periodic hardness surveillance inspections and tests throughout the operational life of the system. Thus, low-risk hardening must be designed to facilitate hardness surveillance inspections and performance measurements and to provide access for repairs when degradations occur.

In summary, a low-risk hardening design must provide effective protection and meet requirements for reliability, maintainability, and testability. A low-risk hardening program must plan and provide the resources for hardening implementation, quality controls including verification testing, and hardness maintenance and surveillance.

6.3.2 **The low-risk approach as applied in MIL-STD-188-125.**

6.3.2.1 **Hardening design features.** The low-risk hardening approach developed in MIL-STD-188-125 for application to fixed, ground-based facilities relies primarily upon the following features for ensuring hardness:

a. Stress control

- An electromagnetic barrier, consisting of a high-quality shield and POE protective devices. The shield is configured to enclose all of the mission-critical systems that will operate satisfactorily and compatibly within the barrier.
- A minimum number of POEs in the barrier.
- Replacement of penetrating conductors with waveguide-protected aperture POEs, whenever practical. Maximum use of fiber optics, pneumatics, and other dielectric means of transferring information through the barrier should be made. Power can also be dielectrically transferred through the barrier using a motor-generator set with a nonconducting shaft or by hydraulics.
- Treatments for each of the POEs in the barrier such that the maximum residual stresses inside the barrier will be below a specified set of allowable levels. The

allowable levels of stress specified in the standard were chosen with the expectation that most MEE will be able to tolerate exposure to any HEMP-induced stresses up to these levels.

- Special protective volumes established for the purpose of isolating regions of high stress from the rest of the protected volume, for those instances in which the POE stress control specifications cannot be met. Each SPV is to be isolated from the rest of the protected volume by introduction of a special protective barrier or barriers.

b. Special protective measures for MEE inside the barrier — Special protective measures applied to MEE in those instances in which the equipment is found to be vulnerable during verification testing. The SPMs will include equipment-level shielding and discrete transient suppression/attenuation devices for additional stress control and, in this case, may involve strength enhancements.

c. Special protective measures for MEE outside the barrier — Special protective measures for MEE which cannot operate inside an electromagnetic barrier. Examples of equipment which must be placed outside the barrier are antennas and perimeter security cameras.

d. Testability and verification testing

- Controls on the number of penetrating conductor POEs in the barrier. The number of these POEs is limited so as to improve reliability and facilitate acceptance, verification, and surveillance testing.
- Accessibility at penetrating conductor POEs to allow connection of pulsed current injection sources and response measurement equipment.
- Sufficient clearance adjacent to the shield surfaces to permit visual inspections and shielding effectiveness measurements.
- Verification testing to confirm stress controls and system hardness or to uncover any remaining vulnerabilities. The verification tests are to include tests to confirm that shielding effectiveness and penetrating conductor POE stress control requirements are still met. Each penetrating conductor is excited at levels up to prescribed levels for the particular type of POE, and the functional response of the system is observed. Special tests are also performed on MEE not contained inside a HEMP barrier. The prescribed excitation levels are intended to represent reasonable worst case stresses that could be imposed by HEMP.

In the complete hardening program called for in MIL-STD-188-125, these features are to be augmented by quality assurance, acceptance testing, and hardness maintenance

and surveillance activities. The hardening approach of the standard makes use of practices that have been used in hardening critical, time-urgent, ground-based facilities in the past. MIL-STD-188-125 formalizes these established practices and makes them mandatory.

6.3.2.2 **Support for hardening program objectives.** This low-risk approach as defined in MIL-STD-188-125 supports the hardening program objectives in the following manner:

a. Design — An effective, low-risk HEMP design is achieved through a combination of verifiable stress control measures. The high-quality shield, with a minimum number of penetrations, and the hardening treatments for every POE create a protected volume enclosing nearly all of the MEE. Special protective measures applied to equipment outside the barrier provide the necessary hardening for these remaining items.

b. Construction — Requirements for hardness assurance inspections and tests during construction ensure proper installation of the barrier and other HCIs. Acceptance testing ensures that the completed HEMP protection subsystem meets the hardness performance requirements.

c. Verification — Thorough verification testing is made practical by the use of a high-quality overall shield and limitations on the number of POEs in the shield. Once it has been established that the shield and aperture treatment components of the HEMP protection barrier adequately attenuate the external stresses, verification testing is reduced to excitation of the penetrating conductor POEs in the barrier. The limited number of barrier penetrations means that every penetration can be physically tested to verify the effectiveness of its treatment. Configuration controls and quality assurance requirements make it highly unlikely that any POEs will be overlooked. Conclusive evidence of protection effectiveness is provided by observing POE treatment effectiveness and actual system functional performance during excitation of conductive POEs at up to worst case HEMP-induced stress levels.

d. Hardness maintenance/surveillance — Reliance on a single-layer shield with a limited number of POEs for protection minimizes the number of hardness critical items whose lifetime performance must be maintained. Hardness surveillance test requirements are also minimized by this design approach; fewer items need to be tested. Accessibility of HCIs, including access for test and maintenance purposes, is a requirement of the standard. The barrier shield also should be designed so that it is accessible for periodic visual inspections. Finally, minimizing the need for equipment-level strength controls will also minimize the need for equipment configuration controls and maintenance.

6.3.2.3 **Advantages.** The low-risk HEMP protection approach as formulated in MIL-STD-188-125 provides a number of significant advantages. These include:

a. The number of HCIs is minimized. Other than the special protective measures for MEE located outside of the barrier, only a single shield or a small number of independent shields and a limited number of POE treatments are to be installed and maintained. As a result, the costs of hardening, testing, and maintaining hardness are minimized.

b. Mission-essential equipment need not be hardened or provided with additional protection unless it is found to be vulnerable during verification testing. As a result, the costs of hardening, testing, and maintenance of hardness for MEE are minimized, if not eliminated. Furthermore, unhardened commercial or non-developmental equipment may be employed as mission-essential equipment within the HEMP barrier. This is important because facilities are often required to use commercial equipment as part of their MEE due to cost, commonality, or other considerations.

c. Facility hardness is not highly sensitive to the location of equipment or to the routing of cables inside the HEMP barrier, as long as the equipment and cables are kept away from the major POEs in the barrier. Thus, there should be no need for internal configuration controls other than keeping cables and equipment away from major POEs in the barrier. The addition of new MEE may, however, trigger the need for reverification of facility hardness during the next regularly scheduled surveillance test (see section 19).

d. Testing is facilitated. The low-risk hardening approach makes reliable testing practical, even for physically large facilities, because the carefully controlled electromagnetic topology allows only a limited number of points-of-entry for HEMP-induced stresses into the system. After confirmation that the shield has met the required shielding effectiveness levels, only the penetrating conductor POEs need be excited during acceptance and verification testing.

6.3.2.4 **Relationship of low-risk approach to other HEMP hardening approaches.** MIL-STD-188-125 hardening can be considered to be a special case of the zonal or allocated approach, having only one protected zone or volume. All of the stress control burden is assigned to a single-layer, high-quality barrier. The barrier specifications are sufficiently stringent that residual electromagnetic stresses allowed in the protected volume are below damage and upset thresholds of essentially all military and commercial communications-electronics hardware. Thus, for fixed, ground-based C^4I facilities, it is not necessary to impose "across-the-board" equipment strength specifications. Additional stress controls

and possible equipment strength enhancements are needed only under highly restricted circumstances requiring SPMs.

An allocated approach with multiple zones and multiple barriers was not adopted by MIL-STD-188-125 for several technical reasons. Multizone hardening would generally require strength controls on hardware to be placed in the outer zones, where transients with larger amplitudes are permitted, and would preclude the use of many commercial C-E equipments in these locations. Furthermore, the number of required HCIs would greatly increase, thus multiplying the time and costs associated with effective hardness assurance, maintenance, and surveillance.

For other applications, such as applications to transportable or mobile, ground-based systems or to aircraft, the optimum hardening approach may be different from the one chosen for fixed facilities. However, any hardening approach for which thorough verification testing and life-cycle surveillance and maintenance are not practical, will be higher risk because of increased potential for undetected degradation.

6.4 **References.**

6-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

6-2. Vance, E. F., "EMP Engineering Practices Handbook," NATO File 1460.3, Supreme Headquarters Allied Powers Europe, Belgium, November 1989.

6-3. Schaefer, R. R., and J. I. Lubell, "Validation of System Hardness to the Nuclear Electromagnetic Pulse (EMP)," DNA-TR-88-161, Defense Nuclear Agency, Washington, DC, 17 June 1988.

7. BARRIER TOPOLOGY DEVELOPMENT

7.1 **Basic principles.** The major steps in implementing a comprehensive hardening program are discussed in section 4. After determining the need for hardening and establishing the hardening requirements, as indicated in figure 1, the first step in the design process (step D1 in figure 1) is to develop the topology of the HEMP barrier. As used in this handbook, the term "topology" refers to the shape of the HEMP barrier, its location in relation to the structures on the site, locations of mission-essential equipment within and outside of the barrier, and the locations of all POEs in the barrier. The barrier topology will have been fully defined when the size, shape, and location of the shield surfaces have been established and the POEs and their locations in the shield surface have been identified.

7.2 **MIL-STD-188-125 requirements.** The MIL-STD-188-125 (reference 7-1) excerpts listed below all have a direct bearing on the topology of the HEMP barrier. They are arranged here in three categories. The first group, in subsection 7.2.1, addresses the general requirements for HEMP hardening. The requirement for an electromagnetic barrier with a minimum number of penetrations is identified, and the criteria for equipment placement with respect to the barrier is established.

The second category, listed in 7.2.2, contains the explicit topological requirements and discusses the penetration entry area. Excerpts in 7.2.3 address special protective volumes and barriers.

7.2.1 **General barrier requirements.**

> *4.1.2 Integration with related requirements. Elements of the HEMP protection subsystem can serve multiple purposes. For example, the electromagnetic* barrier *can also be used to meet emanations security requirements. HEMP hardening measures should be integrated with those of electromagnetic disciplines, such as electromagnetic interference, electromagnetic compatibility, lightning protection, and TEMPEST, and with treatments for other hardening requirements.*

4.3 HEMP hardening design. Facility protection against the HEMP threat environment specified in DoD-STD-2169 shall be achieved with an electromagnetic barrier and with additional special protective measures as required. The electromagnetic barrier shall consist of the facility HEMP shield and protective devices for all POEs. Special protective measures shall be implemented for hardening mission-essential equipment which must be placed outside the barrier and for other special cases to be defined. Reliability (MIL-STD-785), maintainability (MIL-STD-470), safety and human engineering (MIL-STD-1472), testability (MIL-STD-2165), and corrosion control (MIL-HDBK-729) shall be incorporated into the HEMP protection subsystem design.

4.3.1 Facility shield. The facility HEMP shield shall be a continuously welded or brazed metallic enclosure which meets or exceeds shielding effectiveness requirements of this standard (see 5.1.3.1).

4.3.2 Points-of-entry. The number of shield POEs shall be limited to the minimum required for operational, life-safety, and habitability purposes. Each POE shall be HEMP protected with POE protective devices which satisfy performance requirements of this standard (see 5.1.4 through 5.1. 7).

4.3.3 Mission-essential equipment. All equipment required to perform trans- and post-attack missions shall be designated as mission-essential equipment. MEE includes such items as communications-electronic equipment, data processing subsystems, command and control equipment, local portions of hardened interconnects,[3] and critical support subsystems such as power generation, power distribution, and environmental control.

4.3.3.1 Mission-essential equipment within the electromagnetic barrier. All MEE which will operate satisfactorily and compatibly within the facility HEMP shield shall be installed inside the electromagnetic barrier. No HEMP-unique performance characteristics are required in design and selection of mission-essential equipment which will be housed within the barrier.

4.3.3.2 Mission-essential equipment outside the electromagnetic barrier. MEE, such as a radio antenna or evaporative heat exchanger, which must be placed outside the electromagnetic barrier, shall be provided with special protective measures (see 5.1.8) as required to ensure HEMP hardness in the HEMP threat environment.

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[3]Although they are not included within the scope of this document, HEMP-hardened interconnects and survivable long-haul communication circuits to other hardened facilities in the network must be provided as required for mission accomplishment.

7.2.2 **Barrier topology requirements.**

5.1.1.1 Electromagnetic barrier topology. The electromagnetic barrier, consisting of the facility HEMP shield and POE protective devices, shall be configured to accomplish the following technical requirements:

a. To enclose all mission-essential equipment except those equipments such as radio antennas, evaporative heat exchangers, or external security sensors, which will not function properly if placed within the protected volume

b. To minimize the number of POEs

c. To avoid requirements for special protective measures internal to the barrier

d. To facilitate HEMP acceptance and verification testing

e. To minimize requirements for scheduled hardness maintenance

5.1.1.2 Penetration entry area. As a design objective, there should be a single penetration entry area on the electromagnetic barrier for all piping and electrical POEs except those connected to external conductors less than 10 m (32.8 ft) in length. The penetration entry area shall be located as far from normal and emergency personnel and equipment accesses and ventilation POEs as is permitted by the facility floor plan.

7.2.3 **Special protective barrier requirements.**

5.1.8.3.1 Special protective volumes for piping POEs. When a piping POE waveguide-below- cutoff must be larger than 10 cm (4 in) to provide adequate fluid flow and a waveguide-below- cutoff array insert cannot be used, a special protective volume shall be established inside the electromagnetic barrier (figure 6).

5.1.8.3.1.2 Special protective barrier for piping POEs. A special protective barrier shall completely enclose piping which is protected at its POE with a waveguide-below-cutoff larger than 10 cm in inside diameter. The special protective barrier may be a separate shield with protected penetrations or it may be implemented using the metal walls of the piping system itself. Performance requirements for the special protective barrier shall ensure that the total shielding effectiveness, measured through the primary electromagnetic barrier and special protective barrier, satisfies at least the minimum requirements shown in figure 1.

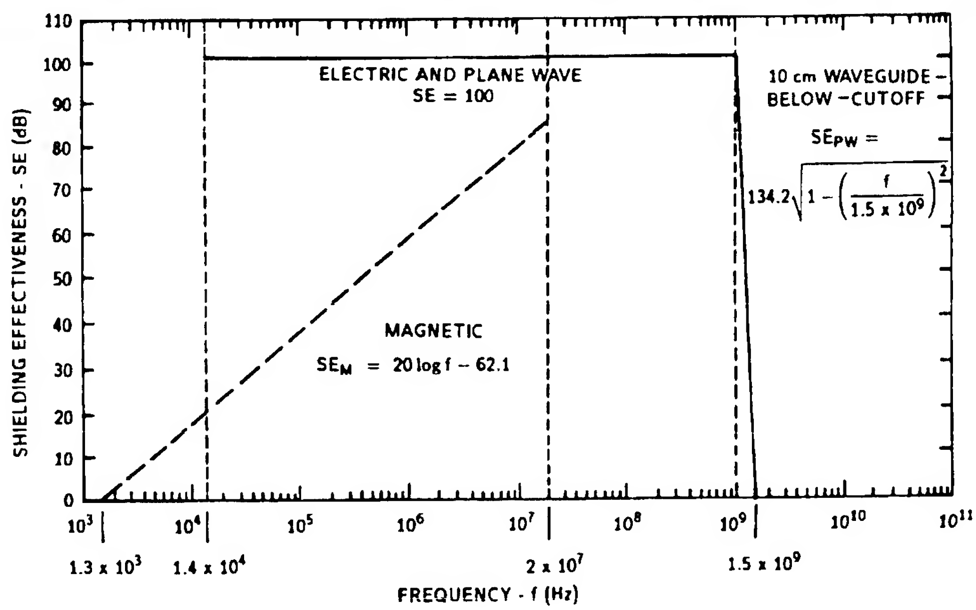


FIG URE 1. Minimum HEMP shielding effectiveness requirements (measured) in accordance with procedures of appendix A).

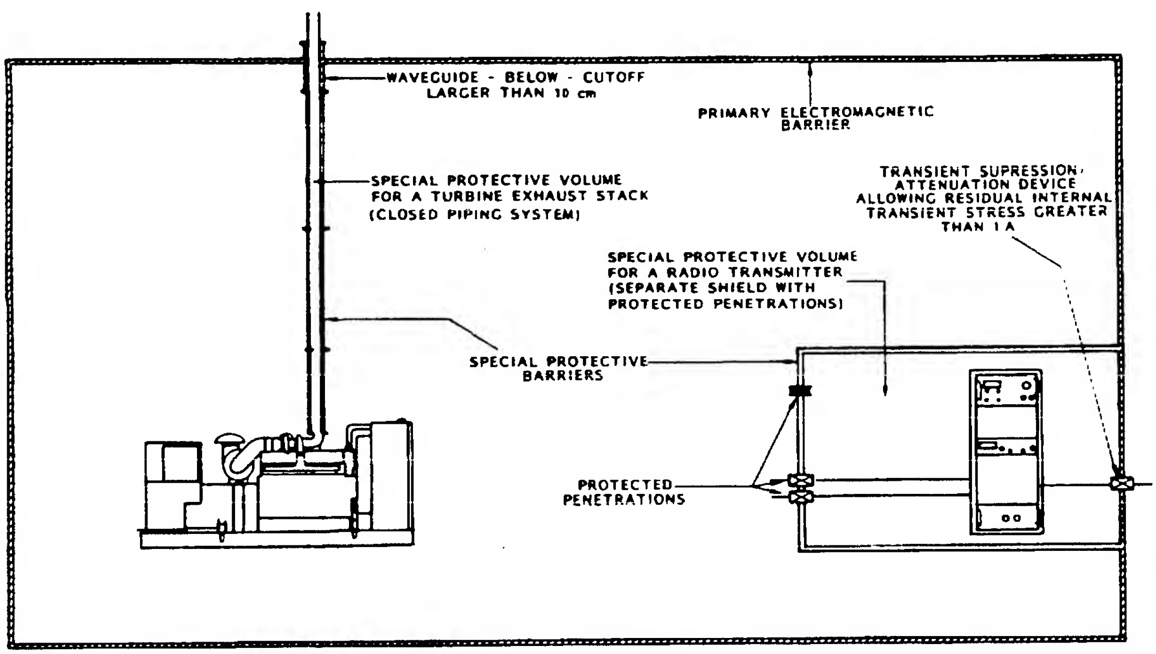


FIGURE 6. Typical special protective volumes.

5.1.8.3.2 Special protective volumes for electrical POEs. When an electrical POE protective device cannot be designed to achieve the transient suppression / attenuation performance prescribed for the class of electrical POE (see 5.1.7) without interfering with operational signals it is required to pass, a special protective volume shall be established inside the electromagnetic barrier (figure 6).

5.1.8.9.2.2 Special protective barrier for electrical POEs. A special protective barrier shall completely enclose wiring and equipment directly connected to an electrical POE protective device which cannot achieve the transient suppression / attenuation performance required by 5.1.7. The special protective barrier may be a separate shield with protected penetrations or it may be implemented using cable and conduit shields and equipment cabinets. Performance requirements for the special protective barrier shall ensure the following:

a. That the total shielding effectiveness, measured through the primary electromagnetic barrier and special protective barrier, satisfies at least the minimum requirements of figure 1.

b. the total transient suppression / attenuation, measured through the primary electromagnetic barrier and special protective barrier, satisfies at least the minimum requirements of 5.1.7.

7.3 **Applications.** In defining the topology of the shield portion of the HEMP protection barrier, it will be necessary to perform the following steps:

a. Identify the equipment that must be enclosed within the barrier-the mission-essential equipment—and determine the expected location of each piece of MEE within the building and on the site.

b. Define the "shield topology," by determining the shape, size, and location of all shield surfaces such that all of the mission-essential equipment are located inside the shield, with exceptions only when allowed by the MIL-STD-188-125 placement criteria.

c. Identify all POEs and their locations in the shield.

Barrier topology development is generally an iterative process. In this process, adjustments are made in the location of MEE and the shield configuration, as needed, to establish the optimum barrier topology. To the extent practical, cables and equipment should be at least one meter from shield walls and POE protective devices. The clearance

facilitates inspections, tests, and maintenance and provides an extra margin of protection in the event of barrier performance degradation.

7.3.1 **Identification and location of mission-essential equipment.** All mission-essential equipment should be identified. This step should be carried out with the assistance of the facility project manager, appropriate system program offices or user organizations, and the system manufacturers. As a first step in this task, the critical, time-urgent missions and supporting functions should be identified. Typical support functions include supply of electrical power, information receipt and transmission, data processing and display, and environmental control. Next, the identification of MEE that performs these functions should be made.

Then, an approximate idea of the locations of the mission-essential equipment on the site should be established. Equipment information in the facility requirements document for a new construction project and initially available to the designer is generally limited to the major C-E and power generation and distribution components. A rough floor plan is created using this data, and preliminary placements of the smaller items such as air conditioning units, power panels, and mechanical systems are determined. Iterations will occur as definition of the equipment suite is refined, but these should be completed prior to the early preliminary design review. The present locations of MEE could be used as a starting point for retrofit hardening of an existing facility.

It may be possible to simplify the problem of providing HEMP protection and reduce the size of the HEMP protection barrier or the number of POEs by relocating the equipment at the site or within the facility. Consideration should be given to adjusting the locations of MEE during the process of shield topology definition.

7.3.2 **Shield topology definition.** Once the mission-essential equipment has been identified and an initial idea of the location of this equipment has been established, the HEMP protection designer can proceed to define the shield shape and size and locations of the shield surfaces. The only HEMP-specific restrictions placed on the topology of the HEMP protection barrier by the requirements of MIL-STD-188-125 are that the barrier must be closed and it must fully enclose all mission-essential equipment except the few components which must be outside to function properly.

The topology of the shield can greatly affect the difficulty, costs, and risks of hardening, and the ability to perform future expansions. Therefore, the shield shape should be developed with consideration given to the tradeoffs between operational impact, cost, and risk. The final equipment placement and shield topology can be expected to evolve as the result of an iterative process in which these factors are taken into account as part

of the overall system engineering. As an additional consideration in defining the shield topology, many facilities which must be protected against the effects of HEMP must also comply with TEMPEST requirements. In these cases, the design and construction methods described in MIL-HDBK-232 (reference 7–2), various military department handbooks and technical letters, and in various National Security Agency documents must be met as well as those of MIL-STD-188-125. In almost all cases, these requirements are compatible, as is explained in sections 8 through 12 of this handbook.

7.3.2.1 **Shield topology options.** Except for openings required for operational purposes, the shield must form a closed metal surface surrounding the mission-essential equip ment to be protected. As long as it meets this requirement, the shield can have any size, shape, or location.

The HEMP hardening engineer tasked with defining the shield topology has three basic options:

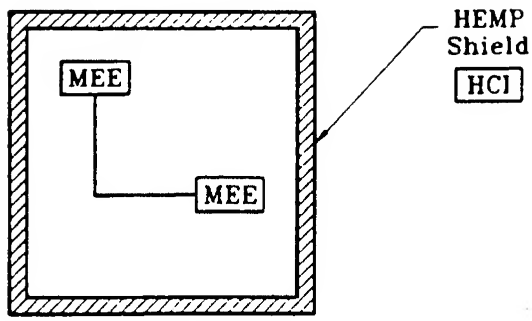
a. Option 1: A single protected volume enclosed within a single shield surface, as indicated in figure 12a.

b. Option 2: More than one protected volume with shield surfaces interconnected by a shielded passageway or welded metal conduits, forming a single shield surface (figure 12 b). Note that transient suppression/attenuation devices are required on the interconnecting wiring, if conduit length exceeds maximum values prescribed in MIL-STD-188-125. This topic will be addressed in section 12.

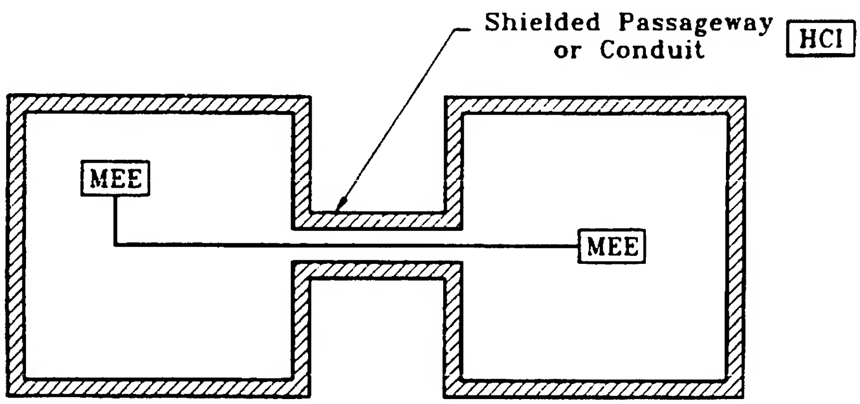
c. Option 3: More than one protected volume, each of which is enclosed by a separate shield surface. The MEE in the separate protected volumes could be interconnected by power and signal conductors which pass through treated POEs in the shield surfaces (figure 12c). If the wiring that is outside the protected volumes is also mission-critical, it must be hardened using special protective measures (see section 14).

In each option, the MEE is fully enclosed within a single-layer shield. The shield surfaces are closed with the exception of the PO ES. The designer chooses among these options based upon factors including cost effectiveness, constructibility, testability, and maintainability.

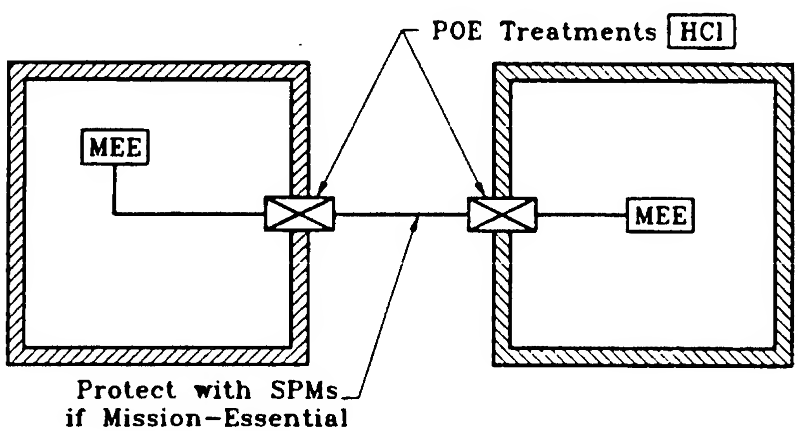
Note that for purposes of simplicity, many pictorial representations of a facility shield, such as figure 12, fail to identify the ceiling and floor surfaces of the shield. Nonetheless, these surfaces must be understood as essential components of the shield. Thus, a box-like shield will have six sides.



a. Option 1: single protected volume.



b. Option 2: two protected volumes connected by passageway or conduit.



c. Option 3: two independent protected volumes.

FIGURE 12. **Shield topology options.**

7.3.2.2 **Shield topology tradeoffs.** Although any one or some combination of these options could be used to satisfy the requirements of MIL-STD-188-125, the choice of shield topology may significantly affect the difficulty and costs of hardening.

A straightforward, but simplistic, topology design approach for a new construction facility is to group the mission-critical systems into a single room, area, or building and to locate noncritical equipment in a separate area. The MEE are then hardened by option 1, enclosing them within a six-sided, box-like shield with protected POEs. This arrangement will usually result in the smallest barrier surface area. It may also require the least number of hardness critical items and, hence, produce the lowest hardening and hardness testing costs.

There are numerous situations, however, that create exceptions to this simple method. Site personnel may require constant or frequent access to noncritical systems during peacetime operations. Option 1 can still be used, but that noncritical equipment should be placed inside the barrier to minimize traffic into and out of the protected volume. Offices, break rooms, and restrooms are often located within the barrier for this reason.

A similar exception occurs when noncritical equipment is highly interconnected with the MEE. Again, the noncritical equipment should be placed inside the single protected volume to avoid additional penetrations and additional HCIs.

Option 2 and its obvious extension to three or more protected volumes are used when, for a variety of reasons, there must be more than one grouping of mission-essential equipment. One common example occurs in retrofit HEMP hardening programs where it would be impractical to relocate all of the installed and existing mission-critical systems into a single area. Other such examples might include the following cases:

a. Sites with several large functional groups such as a command center, a communications unit, and a power plant, each housed in its own hardened building.

b. A small collection of MEE that must be remotely located, away from the main grouping. One specific example is a buried communications facility, with a mission-essential transmitter or antenna tuning unit housed in an aboveground protected volume close to the antenna.

c. A multiuse C^4I facility, where part of the MEE must be physically or electromagnetically isolated from other critical systems for security reasons.

In these cases, welded steel conduits would ordinarily be used to connect the individual protected volumes. HEMP can still couple to cabling within the conduits by field diffusion

through the conduit walls. The amount of coupling increases with increasing conduit length. Therefore, MIL-STD-188-125 contains strict requirements regarding conduit length before transient suppression/attenuation devices are required for each conductor at the entrance to each protected volume.

Option 3 will normally be employed when the individual protected volumes are separated by distances greater than the MIL-STD-188-125 conduit length restrictions. It might also be chosen if one of the clusters of MEE is likely to be moved during the operational life of the facility. It should be recognized that the number of HCIs will increase with option 3. The additional hardening elements are necessary for penetration protection and to harden the conductors running between the shields. Thus, hardening risks and costs will be greater than those of options 1 and 2; option 3 should therefore be avoided if possible.

After choosing among the options, the testability and maintainability factors must be addressed. Clear spaces approximately 1 meter in width should be provided on both sides of the shield surfaces, wherever practical. These spaces will allow unobstructed access for barrier inspections, performance measurements, and repairs. In all cases, at least the minimum access requirements of MIL-STD-188-125 must be satisfied. Further discussion of this topic appears in section 17.

In summary, factors to be considered in selecting the final HEMP barrier topology must include hardness risks, operational procedures, human factors, testability, maintainability, and life-cycle costs for installing, testing, and maintaining the hardness. The 'global barrier" provided under option 1 is generally superior in all of these respects when this option is suitable for the particular site configuration. Other choices should be made only where the advantages clearly outweigh the disadvantages.

Finally, the shield topology should accommodate the ability to make future modifications to the facility. Appropriate provisions for expansion and equipment replacements should be made within budgetary constraints.

7.3.3 **POE identification and placement.**

7.3.3.1 **POE types.** A facility completely isolated from the outside world is of no value in a C^4I system. Because of this, the facility HEMP barrier cannot be formed by use of a completely closed electromagnetic shield. Openings in the shield are necessary to provide for some or all of the following functions:

a. Electrical power service

b. Communications to and from the facility

c. Personnel and equipment entry and exit

d. Equipment service and maintenance, including equipment control lines

e. Heating, ventilating, and air conditioning

f. Fluid (water, sewage) utility connections

All openings in an electromagnetic shield constitute points-of-entry through which electromagnetic energy can potentially be transmitted from outside the shield into the protected volume. Simple holes or cracks in the shield, through which electrical conductors do not pass, are termed inadvertent apertures. Personnel entryways and piping and ventilation openings constitute intentional apertures. POEs through which electrical conductors do pass are termed penetrating conductor POEs. The typical POEs in a fixed, ground-based facility are indicated in figure 13.

Another way of categorizing POEs, and the method used in MIL-STD-188-125, is on the basis of their function in a facility. The standard recognizes and presents requirements for the treatments of four type of POEs: architectural POEs, mechanical POEs, structural POEs, and electrical POEs.

Architectural POEs are intentional openings in the HEMP protection barrier shield. This category includes personnel entryways, emergency exits, and equipment access hatches. Mechanical POEs include openings in the shield to accommodate heating, ventilating, and air conditioning, and plumbing and piping for nonelectrical uses. Structural POEs in the shield are formed when structural elements of the facility penetrate the shield. For example, a steel I-beam serving as part of the facility structure may pass through the HEMP barrier. Electrical POEs are points at which electrical power service lines, equipment control lines, and signal communication lines enter or exit the HEMP barrier.

Architectural and mechanical POEs, if properly designed, constitute aperture POEs. Structural elements that are electrical conductors can, if properly treated, be eliminated as POEs altogether. This requires that the structural element be circumferentially welded to the shield surface. Nonconducting structural elements are not permitted to penetrate the HEMP barrier. Electrical POEs generally constitute penetrating conductor POEs. Exceptions would be the use of fiber optic transmission lines, without any conducting elements, for control and communications and the use of dielectric shafts for power transmission.

Because they generally involve penetrations of the barrier by conductors, electrical POEs constitute the most serious risk to the effectiveness of the HEMP barrier. As such,

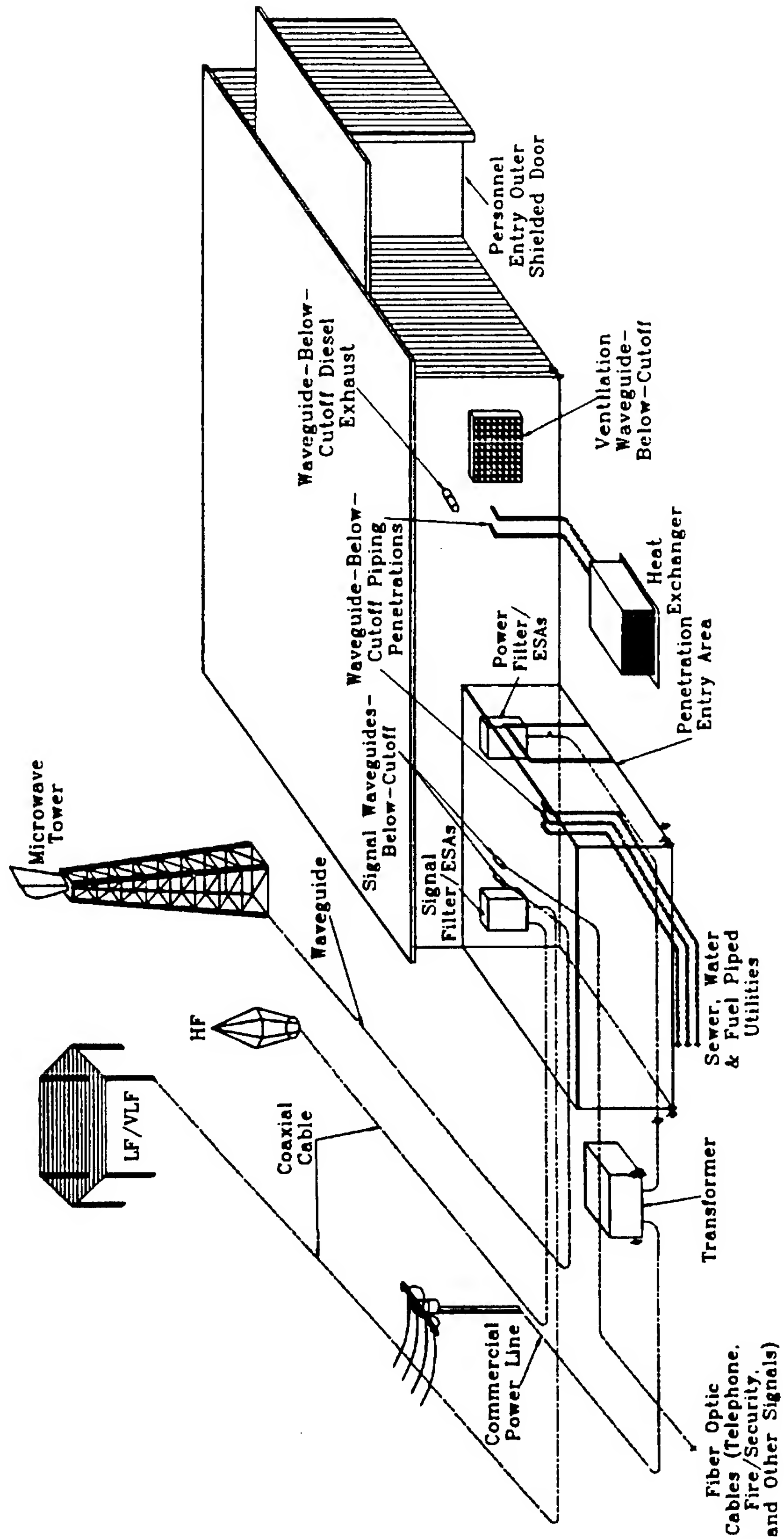


FIGURE 13. Typical POEs for a fixed ground-based facility.

FIGURE 13. Typical POEs for a fixed ground-based facility.

they should receive the highest priority for identification and treatment in the hardening design, after establishment of the shield itself.

7.3.3.2 **Identification of POEs.** As part of the barrier topology development, the POEs that will exist in the HEMP protection barrier must be identified and assigned locations. This step can be initiated by first identifying the services and functions that must be supported at a facility and determining whether each service or function is mission-critical. Next, the number and type of POEs required to support each of these services or functions should be identified.

In view of the adverse impact of POEs on hardening costs and risks, wherever possible the designer should minimize the number of POEs in the HEMP shield by eliminating any unnecessary POEs and converting penetrating conductor POEs to lower risk POEs. POEs can sometimes be eliminated by means of line routing and signal multiplexing. Conversion to lower-risk POEs can be achieved by replacement of telephone or other signal lines with fiber optic lines and by use of dielectric power transmission.

7.3.3.3 **POE location and grouping.** MIL-STD-188-125 states as a design objective that there should be a single penetration entry area on the electromagnetic barrier for all piping and electrical POEs except those associated with conductors less than 10 m (32.8 ft) in exposed length. The rationale for this goal is that currents induced by HEMP on long conductors connected to the barrier will tend to flow onto the exterior of the barrier shield. If different conductors are attached to the shield at widely separated points, the surface currents will be inclined to flow over much of the shield surface. As a result, any imperfections in the shield between the connection points will be excited by the surface currents and associated fields. These fields might penetrate the shield at the imperfections and couple to conductors inside the facility. By restricting the location of the entry and exit points for all long conductors to a single area—away from doors and other openings—and by providing extra shielding over this area, this potential contribution to interior stresses can be minimized.

The PEA design must incorporate sound electromagnetic compatibility practices to preclude excessive cross-coupling from the relatively high HEMP-induced stresses on power lines and long metal pipes to control and data lines, which carry low-level signals. Separate areas within the PEA should be established for the power, piping, and signal line penetrations. Low-level signal lines should be shielded or enclosed in metal conduits. Alternatively, the different areas may be electromagnetically isolated from each other by use of additional shield surfaces. The PEA should also be located as far as practical from major aperture POEs such as the personnel entryway and ventilation penetrations, as illustrated in figure 14.

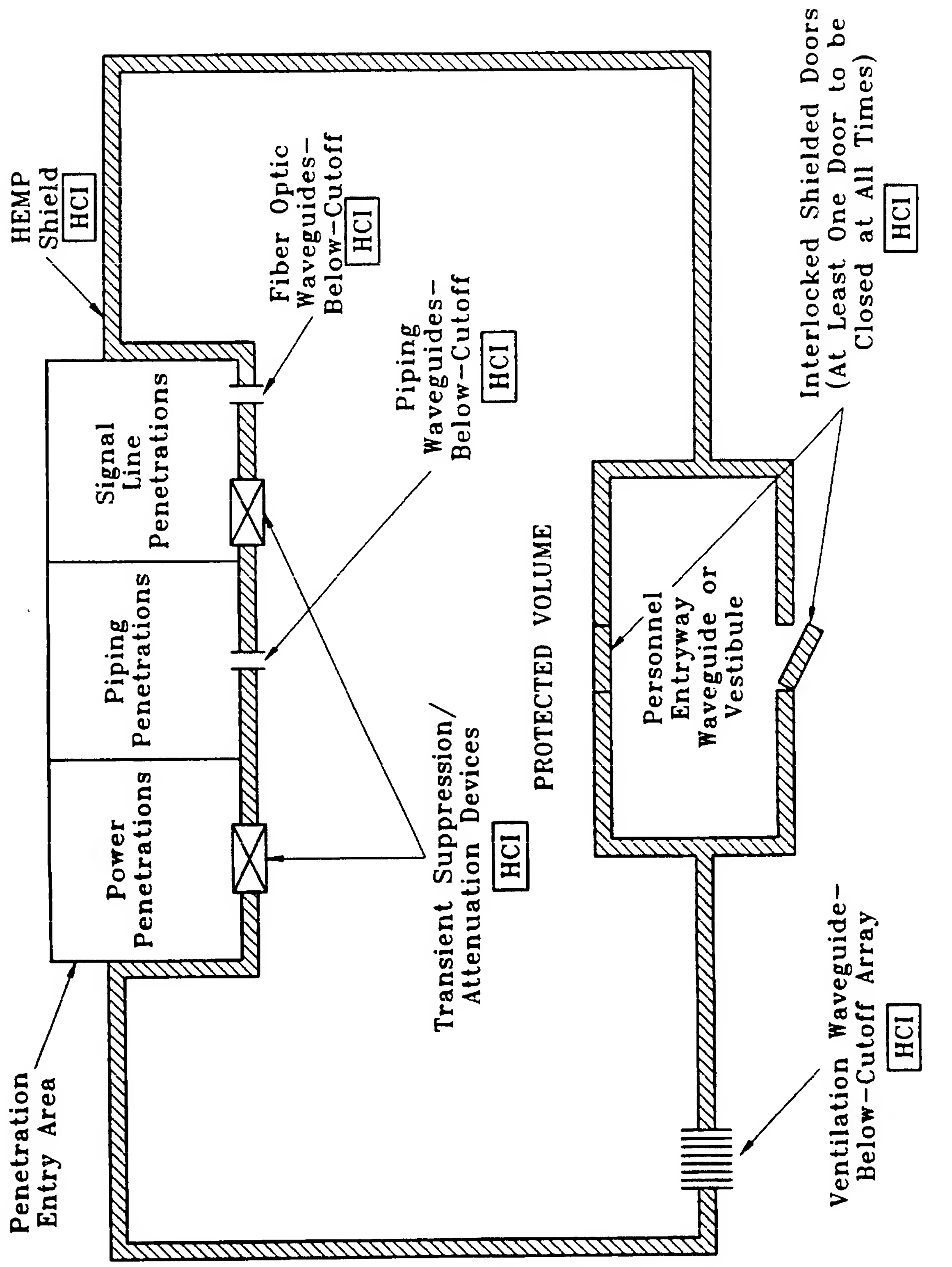


FIGURE 14. Penetration entry area and major aperture POE locations.

FIGURE 14. Penetration entry area and major aperture POE locations.

7.3.3.4 **POE control procedures.** In order to control the number and types of POEs, as required by MIL-STD-188-125, it is recommended that a schedule of barrier POEs be prepared. This schedule should identify all POEs, grouped in accordance with the four categories discussed above and each POE annotated in terms of its function, location, and the expected type of protection. This schedule should include each door, hatch, vent, pipe, conduit, and electrical line penetration. A sample schedule containing the penetrations previously shown in figure 13 is presented in figure 15.

The first draft of the POE schedule should be carefully examined to determine if any penetrations can be eliminated by combining functions or making other changes in design. Options for eliminating electrical penetrations include eliminating the function supported by the conductor, replacing the conductor with a nonconductor by using optical fibers for data transmission, or peripherally bonding the conductor to the shield at the penetration so as to effectively eliminate the penetration.

In addition to the penetration schedule, a separate schedule of filters and ESAs required for electrical POE protection should be included in the electrical drawing package (figure 16). Each electrical POE should be identified by the same designation that appears in the penetration schedule, and the number of penetrating wires should be shown. Key information including maximum operating voltage, maximum current, and the frequency range of operating signals should be provided for each penetrating conductor. Filter information to be provided should include passband and rejection band frequency ranges, maximum insertion loss in the passband, minimum insertion loss in the rejection band, and image impedance when applicable. The required breakdown voltage range for the spark gap (or range of varistor voltages at 1 mA dc current for an MOV) and the extreme duty discharge current should be indicated for the ESA. Unusual requirements, such as a stringent limit on the reactive current leakage of the filter or exceptionally high terminal strength specifications, should be identified in the notes.

7.3.4 **Special protective measures and volumes.** The MIL-STD-188-125 requirements for the use of special protective measures are discussed in detail in section 14 of this handbook. However, these requirements can impact the topology of the HEMP barrier, and they must be addressed here as well.

Special protective measures must be employed in response to three different situations:

a. When mission-essential equipment must be located outside the electromagnetic barrier (case 1)

Penetration Number	Description	Penetration Location		Penetration Treatment	
		Room/Surface	Drawing	Type of Protection	Detail Drawing
A 1	Inner door	Waveguide entryway	A 1	Shielded door	A 5 (door schedule)
A 2	Outer door	Waveguide entryway	A 7	Shielded door	A 5 (door schedule)
M 1	10 cm waste water line	PEA	A 7	Piping WBC	M 13
M 2	5 cm domestic water line	PEA	A 7	Piping WBC	M 13
M 3	5 cm fuel supply line	PEA	M 2	Piping WBC	M 13
M 4	5 cm chilled water supply line	Generator room/south wall	M 8	Piping WBC	M 13
M 5	5 cm chilled water return line	Generator room/south wall	M 8	Piping WBC	M 13
M 6	1 m × 1 m generator room ventilation panel	Generator room/south wall	M 10	WBC array	M 14
M 7	10 cm generator exhaust pipe	Generator room/south wall	M 10	Piping WBC	M 13
E 1	Commercial power line	PEA	A 7	Filter/ESA	E 9
E 2	Fiber optic cables	PEA	A 7	Signal WBC	E 9
E 3	VLF/LF communications	PEA	A 7	Filter/ESA	E 9
E 4	HF communications	PEA	A 7	Filter/ESA	E 9
E 5	Microwave communications	PEA	A 7	Communications WBC	E 9

FIGURE 15. **Sample shield penetration schedule.**

Penetration		Operating Parameters				Filter Parameters		ESA Parameters		
Number	Description	Voltage	Current	Frequency	# of Wires	Passband/ Attenuation	Stopband/ Attenuation	Type	Breakdown Voltage	Extreme Duty Current
E 1	Commercial power line	480 Vac	800 A	60 Hz	4	40–100 Hz ≤ 0.5 dB	14 kHz–1 GHz ≥ 100 dB	MOV	580–980 V	70 kA
E 3	VLF/LF	35 Vac	1 A	70–80 kHz	1	70–80 kHz* ≤ 0.5 dB	200 kHz–1 GHz ≥ 100 dB	Spark gap	75–125 V	10 kA
E 4	HF	1000 Vac	20 A	10–30 MHz	1	10–30 MHz* ≤ 0.5 dB	14 kHz–1 MHz and 100 MHz–1 GHz ≥ 100 dB	Spark gap	2100–3500 V	10 kA

NOTES:

*Image impedance = 50 Ω; voltage standing wave ratio ≤ 1.5:1

FIGURE 16. Sample filter/ESA schedule.

FIGURE 16. Sample filter/ESA schedule.

b. When mission-essential equipment inside the electromagnetic barrier is found to be susceptible during verification testing (case 2)

c. When POE treatments cannot be designed in conformity with, or to meet the specifications of, the standard (case 3)

An example of case 1 is a satellite earth terminal with its large antenna outside the protected facility. The antenna, a two-story structure containing complex electronic equipment, is clearly mission-essential equipment, and must be protected from HEMP effects. Obviously, the antenna component of the earth terminal cannot be completely enclosed within an electromagnetic barrier. However much, if not all of the associated electronic equipment can be made to operate inside a HEMP barrier, and must be protected by means of such a barrier. The special protective measures for an antenna might include antenna design and materials selection to prevent arcing and resulting damage.

Case 2 addresses the situation in which an item of mission-essential equipment is found to be unable to withstand and operate through the residual stress levels within the facility. Any such electromagnetically fragile MEE is to be finally identified during verification testing, when the electrical conductors entering the facility are subjected to threat-level HEMP-like pulses, as described in section 16. However, it might also be identified earlier, during the design and construction of the facility. Protection for this fragile equipment might involve erection of an additional barrier around the equipment.

Case 3 has the most relevance to the topology of the HEMP barrier. The protection standard calls for the establishment of special protective barriers within the facility primary barrier so as to contain any stresses that exceed the allowable values within a limited volume (the special protective volume). The intent is to ensure that these high-level stresses do not propagate any further than necessary within the larger protected volume. Special protective barriers are required when:

a. Piping or waveguides must be larger than the required 10 cm, due to other operational reasons

b. Electrical POE treatments cannot prevent stresses at levels above the specified limits from entering the facility. For example, HEMP-induced coupling to a radio antenna may be large and, because of the required rf passband, HEMP-induced stresses in excess of the allowable levels may be allowed past the POE protection.

Examples of the formation of special protective volumes are illustrated in MIL-STD-188-125, as well as in section 14. In each case, the special protective volume is to be established by formation of a special protective barrier inside the primary barrier. The

shield components of the SPB may be formed by use of a special shielded enclosure or by incorporation of existing cable shields or conduits and continuation of shield elements into the interior of the building.

The barrier topology should be defined for each of the SPBs as a part of the overall HEMP barrier topology development. The SPB topology definition should include the location of all shield surfaces and all POEs leading into the protected volume side of the barrier. Finally, any SPB POEs should be accounted for in the overall POE schedule.

The requirements for special protective measures, volumes, and barriers should be identified as early in the hardening design process as possible so as to minimize construction costs and the likelihood of adverse schedule impact. The HEMP hardness designer should be able to anticipate requirements associated with cases 1 and 3 by reference to equipment specifications, discussions with the system program management and the system engineer, and information from past hardening and test programs. The case 2 requirements may not be identifiable in advance of verification testing, although experience from past test programs may provide relevant information.

MIL-STD-188-125 states that the facility HEMP barrier is to be configured "in a way that will avoid requirements for special protective measures. While these measures will be necessary in certain cases, as noted above, each represents a complication in the design, fabrication, testing, and maintenance of the barrier. The designer should strive to keep these complications to a minimum.

7.3.5 **Power generation and distribution system.** A proper design of the site power generation and distribution system for a critical, time-urgent C^4I facility is an essential element in providing effective HEMP protection. Because of the extreme size and the overhead conductor configuration of commercial power grids, the HEMP-induced transient on the site commercial power feeder or feeders may be large and may include components due to the early-time, intermediate-time, and late-time threat environment. HEMP coupling to the commercial power network may also produce distorted waveforms or loss of the commercial source. The facility power generation and distribution system must be designed to permit essential mission operations to continue under any of these circumstances.

A simplified schematic diagram of the power system HEMP protection concept is shown in figure 17. The drawing is intended to highlight the HEMP protection features only. Conventional electrical design information such as bus configurations, metering and relaying, and load distribution should be obtained from other sources, including references 7-3 and 7-4. The three key elements of the HEMP protection concept are com-

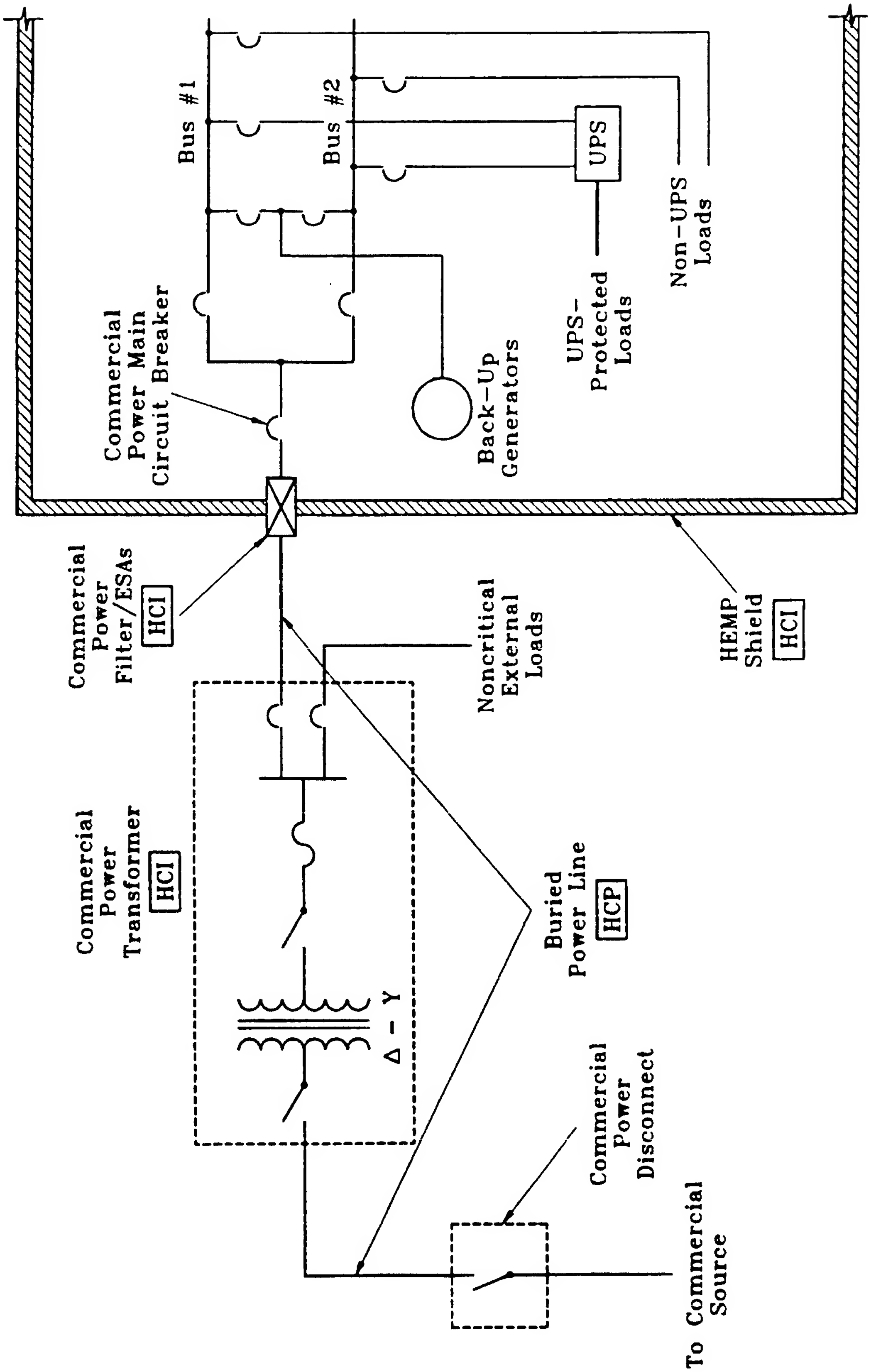


FIGURE 17. Simplified power generation and distribution schematic.

FIGURE 17. Simplified power generation and distribution schematic.

mercial power line POE treatment, provisions for hardened backup power sources, and minimization of barrier penetrations.

The power line POE protection includes the commercial power disconnect, power line burial, the site commercial power transformer, filter/ESA transient suppression/ attenuation devices, and the main circuit breaker. Detailed requirements for these hardening elements are discussed in section 12; related general principles include the following:

a. A means of remotely opening the disconnect switch and preventing inadvertent reclosure should be provided at a location within the HEMP barrier. Additionally, if the facility has a reliable nuclear event sensor, the disconnect switch should be automatically opened when the HEMP environment is detected.

b. The incoming commercial power feeder must be buried for at least 15.2 m (50 ft). The buried length may be between the penetration entry area and the transformer, on the source side of the transformer, or any combination of these two segments. In the event of physical constraints which preclude a straight 15.2 m buried length, the buried line may be 'snaked," with a spacing of at least 1 m (3.3 ft) between adjacent sections.

c. The delta primary-wye secondary winding configuration is a critical feature for long pulse protection.

d. The surge arresters and filters must be capable of attenuating the reasonable worst case, 4 kA short pulse transient to residual internal stress levels below the limits specified in MIL-STD-188-125.

e. A power quality monitor and a commercial power circuit breaker with at least overvoltage, undervoltage, overfrequency, and underfrequency trip circuits should be provialed in the main switchgear.

A self-supporting power generating capability is essential for operations in the event that commercial power is unavailable. The required capacity and endurance of the backup power system should be clearly defined. This capability will typically include both fossil-fueled prime mover-generator sets and an uninterruptible power source (UPS), as well as hardened support equipment such as fuel system and heat removal system components. The backup power equipment must be designated as MEE. This designation implies that the equipment must be located within the HEMP barrier, unless it cannot operate satisfactorily inside a shield. Components that must be placed outside the barrier are HEMP-hardened using special protective measures (see section 14).

It is recommended that capabilities to parallel commercial power and the backup generators and to operate with these two sources in parallel be provided. These capabilities will permit pulsed current injection tests required by MIL-STD-188-125 to be performed with minimum impact on normal site operations. When such parallel operation is possible, proper fault protection and coordination including directional relays must also be provided in the design.

POE minimization is achieved by supplying power to noncritical external loads from an external feeder and distribution panel. If backup power is required in non-HEMP situations for these loads, an external generator set should also be provided.

7.4 References.

7-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

7-2. "Military Handbook - Red/Black Engineering: Installation Guidelines: MIL-HDBK-232 (effective), Dept. of Defense, Washington, DC.

7–3. "Policy Guidelines for Installation Planning, Design, Construction and Upkeep," DoD Manual 4270.1-M (effective), Dept. of Defense, Washington, DC.

7-4. "Major Fixed Command, Control, and Communications Facilities Power Systems Design Features Manual," HNDSP-82-043-SD, U.S. Army Engineer Division, Huntsville, AL, August 1986.

8. SHIELDS AND SHIELDING

8.1 **Basic principles.** The HEMP shield serves three functions as part of the HEMP barrier:

a. It prevents potentially damaging radiated electromagnetic stresses from reaching sensitive equipment in the protected volume by field reflection and attenuation.

b. HEMP-induced transients on exposed metal pipes and electrical conductors are deposited on the outer shield surface by the actions of POE protective devices and prevented from entering the protected volume by the skin effect.

c. The shield limits the number of ways that electromagnetic energy can enter the facility.

For these reasons, the shield can be said to be the primary element of the electromagnetic barrier. The shield, exclusive of the penetrating conductor and aperture treatments, consists of the metallic enclosure portions of the electromagnetic barrier. The role of the shield is to exclude electromagnetic fields from the protected volume of the facility. The shield acts to reflect the incident fields and severely attenuate those fields and currents that penetrate into the metal.

To be effective, the shield must exclude or greatly attenuate incident electric and magnetic fields. To accomplish this, electromagnetic shielding surrounds a volume with a conductive layer on which highly mobile electrons can arrange themselves and produce surface currents and charges that oppose the incident fields. This is known as the Faraday cage principle. External electric fields perpendicular to the surface are terminated on surface charges that form on the shield as its free electrons respond to the incident field. The tangential electric field is shorted and reflected by the conductive shield. Magnetic fields perpendicular to the surface induce eddy currents in the shield's surface. This, in turn, produces a magnetic field that opposes the incident field in and beyond the shield (inductive magnetic shielding). The tangential magnetic field induces current in the shield, which in turn produces a magnetic field that adds to the incident field (field doubling).

The essence of a good shielding layer is the maintenance of good electrical conductivity, or low resistance, over all portions of the surface. Leakage through a shield surface occurs to the extent that voltages develop across resistances or impedances in the surface, and these voltages act as sources to reradiate fields into the interior of the shielded volume. The bulk of the shield surface will be made up of metal sheet. Continuous metal sheet of thickness greater than about 0.25 mm or ten thousandths of an inch is sufficiently

impervious to HEMP that the residual transients induced by the fields penetrating the metal wall will be negligible. A shielding effectiveness calculation for the bulk metal shows that the attenuation requirements are satisfied by virtually any metal in a thickness that allows handling. Therefore, mechanical considerations and costs are the primary factors in choosing the type of metal and thickness. Where there is continuous metal sheet, the shield will be adequate; only the openings and discontinuities in the metal require further attention.

The magnetic shielding effectiveness of a closed spherical shell of radius a and wall thickness d is given by the following equation from reference 8–1:

$$T = \frac{H_i}{H_o} = \left[\cosh\sqrt{s\tau_s} + \frac{1}{3}\left(K\sqrt{s\tau_s} + \frac{2}{K\sqrt{s\tau_s}}\right)\sinh\sqrt{s\tau_s}\right]^{-1} \tag{6}$$

where H_i is the magnetic field inside the shield and H_0 is the uniform incident field outside the shield. In equation 6, the complex angular frequency $s = iw$ where $i = \sqrt{-1}, w = 2\pi f$, and f is the frequency. Diffusion time $\tau_s = \mu\sigma d^2$, where μ is the permeability of the shield metal and σ is the conductivity. Permeability $\mu = \mu_r\mu_o$, where μ_r is the relative permeability of the metal and $\mu_o = 4\pi \times 10^{-7}$ is the permeability of vacuum. The dimensionless geometric parameter $K = a/\mu_r d$; it can also be expressed in terms of the volume V and surface area S of the sphere as follows:

$$K = \frac{3V}{\mu_r S d} \tag{7}$$

The shielding effectiveness of the closed spherical shell is plotted in figure 18 as a function of the normalized frequency $\omega\tau_s$, with K as a parameter.

Reference 8-1 also indicates that the effectiveness for a nonspherical shield can be approximated by that of a spherical shell with the same volume-to-surface ratio and the same wall thickness. Thus, for a cubic shield with sides of length A and wall thickness D, the equivalent geometric parameter $K_e = A/2\mu_r D$.

A practical example illustrates the point of this theoretical discussion. For a mild steel shield of typical construction sheet thickness, diffusion time τ_s will be in the range of 1×10^{-4} seconds to 1×10^{-2} seconds. The equivalent geometric factor K_e for a single story, moderately sized building shielded with mild steel will be in the range of 30 to 1000. Figure 18 shows that the performance obtainable from a mild steel shield without holes can easily meet the requirements specified in MIL-STD-188-125 (reference 8–2).

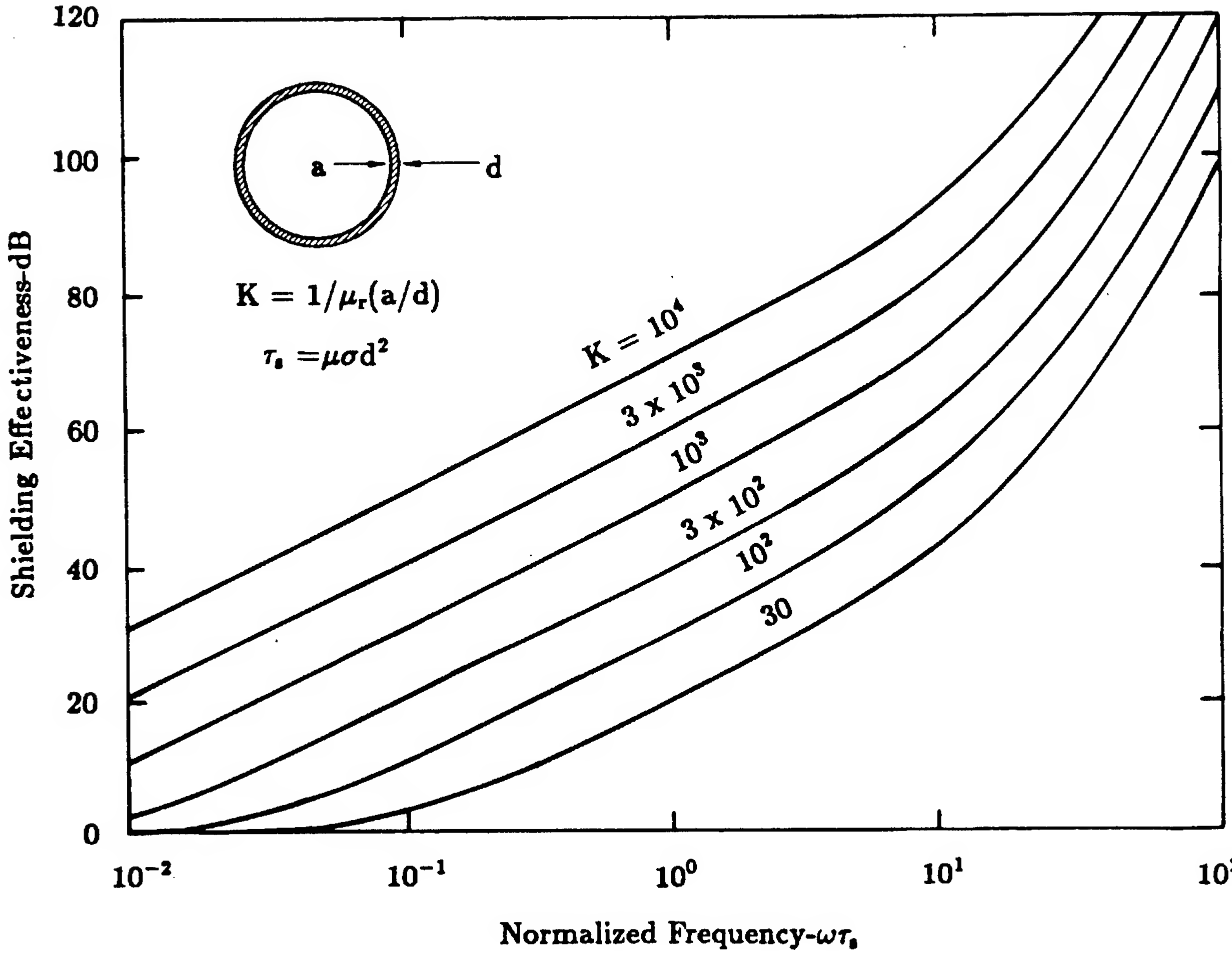


FIGURE 18. **Magnetic shielding effectiveness of spherical shell enclosure versus normalized frequency for various values of parameter *K*.**

8.2 **MIL-STD-188-125 requirements.**

4.3.1 Facility shield. The facility HEMP shield shall be a continuously welded or brazed metallic enclosure which *meets or exceeds shielding effectiveness requirements of* this *standard (see* 5.1.9.1).

5.1.3 *Facility HEMP shield.*

5.1.3.1 Shielding effectiveness. The facility HEMP shield, with all POE protective devices installed, *shall provide at least the minimum shielding effectiveness shown in figure 1.*

5.1.9.2 Shield construction. The facility HEMP shield, exclusive of its POEs, shall be a continuous steel or copper enclosure, closed on all wall, ceiling, *and floor surfaces. All seams and joints between adjacent panels shall be continuously welded (for steel* shields) *or continuously brazed (for copper shields). Welding and brazing shall be performed using procedures and personnel qualified* in *accordance with MIL-STD-248.*

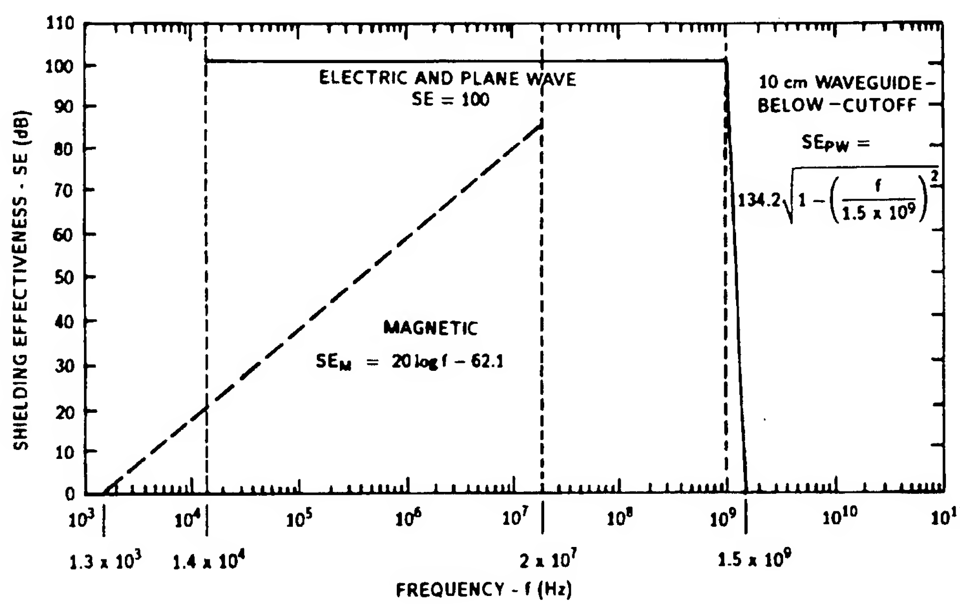


FIGURE 1. ***Minimum HEMP shielding effectiveness requirement (measured in accordance with procedure of appendix A).***

8.3 **Applications.** A number of factors must be considered in the design and construction of the shield:

a. The general shield design problem, including shield testability and maintainability; for instance, MIL-STD-188-125 requires space above the shield ceiling for inspection of the shield

b. Shield material thickness

c. Welding

d. Shield seam construction

e. Corrosion control and other life-cycle shield problems

f. The shield/POE treatment interface

g. The shield/structure interface

h. Quality assurance inspections and tests during shield construction

The text addresses these issues, with a principal emphasis on welded steel shields. Brazed copper shields are then discussed in subsection 8.3.6. The terms "weld," "welded," and "welding" are also used in this and later sections of the handbook in a generic sense to discuss topics that apply to both steel and copper shields. In such contexts, these terms should be interpreted to include brazing.

Shield testability and maintainability are extremely important HEMP protection subsystem characteristics. As a minimum, MIL-STD-188-125 requires access for visual shield inspections at all POEs and from the crawl space above the ceiling shield. The design must also provide access to perform shielding effectiveness measurements. Testability and maintainability are significantly enhanced, however, when all shield surfaces can be visually examined from both sides. Wherever possible, therefore, the shield surfaces should be available for viewing (see section 17).

The use of a concrete wear slab poured on top of the floor shield is another topic for general discussion. Because of unevenness in the floor shield surface due to weld beads and plate shaping, warpage, and buckling, wear slabs have been installed in several past projects. Monitoring and repair of the floor shield in these facilities is difficult and expensive. Therefore, wear slabs are discouraged unless absolutely necessary. Raised floors should be used in electronics and administrative spaces. Steel deck plate installations can be used in machinery spaces, and drip pans should be provided where water leakage is

anticipated. If a wear slab must be used, a vapor barrier should be placed between the shield and the slab and a water seal should be applied to the concrete surface.

8.3.1 **Shield material and thickness.** HEMP protection requirements for the minimum thickness of the shield are usually satisfied by structural considerations, since the shield metal requires a degree of structural rigidity. The shield required by MIL-STD-188-125 is a high-quality, closed electromagnetic barrier that nominally provides 100 dB attenuation, measured in accordance with the procedures described in section 16. (The nominal SE is the electric or plane wave shielding effectiveness in a midfrequency range of 10-100 MHz; the magnetic SE or electric/plane wave SE at lower or higher frequencies may be different from the nominal value.) The shield will generally be constructed using 1.5 mm to 6.4 mm (0.06 in to 0.25 in) thick steel sheets. Seams between sheets must be joined by continuous welding or brazing, as required in MIL-STD-188-125. Smaller sheets are less subject to warpage due to transport or welding, but require more welds per unit area. The material cost may be lower for thinner stock, but thicker sheets may be easier to handle and assemble, since welded bonds are required. The thicker sheets also have better structural properties and are less vulnerable to in-service damage.

The final selection of the shield thickness is often determined by considerations of cost, availability, ease of handling, and structural requirements, rather than by electromagnetic properties. Steel that is sufficiently thick for welding provides more than adequate reduction of the HEMP fields. Some additional guidelines for selection of shield materials and thickness are:

a. Common sheet steel should be used whenever possible; however, corrosion requirements or other needs may dictate the use of stainless steel (see section 15). The MIL-STD-188-125 requirement for steel or copper for shields does not preclude the use of stainless steel.

b. The material must be sufficiently thick to insure good HEMP welds and have adequate strength and rigidity to be mechanically sound.

c. The material should be galvanically compatible with metals that will be used in aperture and penetration treatments.

Steel plates are normally fabricated in accordance with ASTM A6/A6M (reference 8-3) or ASTM A36/A36M (reference 8-4). These are standard specifications for rolled steel plates and bars for structural use. When specifying a size and thickness of steel plate for HEMP shield use, the designer should be aware that, for instance, ASTM A6/A6M allows a 6.4 mm (0.25 in) carbon steel plate that is 2.4 m (8 ft) wide to vary up to 4.1 cm (1.6 in) from flatness. If the plate is to be used for the floor shield over a concrete subfloor,

this unevenness can be the cause of assembly difficulties. The slab thickness and the anticipated floor load must be taken into account when specifying this plate, especially in generator rooms and other areas with heavy equipment and wheeled loads.

While increased thickness can improve the shielding effectiveness of a continuous metal enclosure, this cannot be used to compensate for lack of protection on apertures and penetrations. Increased material thickness can be used to advantage at the penetration entry area, because of the large HEMP-induced currents that will be deposited there. A single PEA is used in the low-risk approach to group together the external conductors that must enter the facility (see section 12). The PEA serves two functions: it causes all external conductor currents to enter or leave in one region of the shield, so that these currents do not flow over the entire shield, and it provides a controlled region on the shield for the high-density currents delivered by the external conductors.

A low-carbon steel is preferred, where feasible, because of its relatively low material cost and excellent shielding properties. As a minimum, low-carbon steel sheets should be painted after installation. They may also be shop-galvanized in selected cases for corrosion protection. (See section 15 for more information on corrosion control of shield elements.) Welded seams and joints are required to reduce risk due to uncertainties in the life-cycle performance of bolted joints. Shields with bolted joints, foil shields, and spray-on shields are not considered adequate due to problems with reliability and maintainability.

Stainless steel sheets are approximately four times more expensive than low-carbon steel sheets of the same size, and they are more difficult to weld. In particularly corrosive environments, however, these disadvantages may be offset by reduced maintenance requirements. If the use of stainless steel is being considered, it is very important that the designer choose an alloy that offers the best combination of availability, weldability, corrosion resistance, and cost. Ferritic 430 series stainless steel has been successfully used as a HEMP shield material on several past projects. It was chosen as a candidate material for its superior corrosion resistance, due to the high (16 percent) chromium content. It has also been found to be readily available in the appropriate sheet sizes, and has proven to be satisfactory in the sense of weldability.

The shield construction techniques suggested in this handbook should be considered as examples only. The designer should investigate alternative assembly methods, using the following criteria and guidelines:

a. Use the largest steel plates practical, in order to minimize the total length of welds to be made.

b. Integrate shielding material into the design of the facility.

c. Select materials and design assembly details for ease of welding or brazing.

d. Where possible, employ assemblies that can be prefabricated in the shop to enhance the weld quality.

e. Investigate the possibility of using automated welding or brazing

f. Include provisions for thermal expansion and contraction in the shield design.

It is also suggested that the construction specifications permit minor deviations from the drawings by the shielding contractor, with approval of appropriately knowledgeable architectural-engineering and Government personnel, so the shield can be fabricated more easily.

8.3.2 **Welding.** The manner in which separate sections of the shield are joined together and shield sections are joined to the POE treatments is crucial to the effective functioning of the barrier. Approaches that employ bolts or rivets obtain an electromagnetic seal by metal-to-metal contact of clean, unpainted, and unoxidized surfaces or special gaskets designed for shielding applications. Inherently, such methods produce joints with lower shielding quality than the basic sheet material, as well as lower quality than welded and brazed joints. Welded or brazed joints, in contrast to mechanically fastened joints, are potentially as high in technical quality and as undemanding of maintenance as the sheet material. By nature, they are much less susceptible to gradual, unseen degradation. Thus, while initial investment may be somewhat greater for welded or brazed joints, life-cycle costs will be very much less. In summary, continuous metal joints are superior to mechanical fastening techniques in technical quality, ease of maintenance, and life-cycle Costs.

Workers who are to weld and braze a HEMP shield should be qualified to MIL-STD-248 (reference 8–5). Welding of thicker sheets should be done in accordance with the general provisions of ANSI/AWS D1.1 (reference 8-6), which describe procedures for welding carbon and low alloy steel greater than 3 mm (0.12 in) thick. ANSI/AWS D1.3 (reference 8–7), ANSI/AWS D9.1 (reference 8–8), MIL-STD-1261 (reference 8–9), MIL-STD-1892 (reference 8–10), and MIL-STD-2219 (reference 8-11) also describe welding processes, methods, and materials.

The shield welds are critical to the achievement of shielding effectiveness, so good welding practices are essential. Because welding is such a large part of the process of

erecting high-quality enclosures, it is well to consider the types of welding techniques that have been found to produce good results.

The heat from welding also tends to cause the sheets to expand and buckle; this is the most severe shield assembly problem encountered in many projects. The subject is separately addressed in subsection 8.3.5.

8.3.2.1 **Shielded metal-arc welding.** Shielded metal-arc welding is one of the oldest arc welding methods. It uses a covered electrode consisting of a core wire surrounded by a hard concentric coating of a flux material. At the arc, the heat causes the coating to generate gases that stabilize the arc. Gases that exclude the ambient atmosphere from the weld area and slag to protect the weld during cooling are also produced in this process. The electrode also supplies the material to alloy the weld.

Shielded metal-arc welding is not desirable for general shield welding because the slag is easily entrapped in the weld, possibly causing rf leaks. It can be used with care to repair leaks, because only the welding electrode needs to be transported from hole to hole. It is also useful for welds in tight spaces, where a metal inert gas (MIG) gun nozzle cannot fit.

8.3.2.2 **Gas metal-arc welding.** For general welding of thin sheet metal shields, welding with a short-circuiting gas metal-arc or MIG process is the most desirable. In MIG welding, the welding wire is automatically fed through the welding nozzle, where it serves as the electrode and the filler material. A shielding gas is also provided through the nozzle automatically.

The shielding gas not only protects the arc and the weld zone from the air, it influences the characteristics of the arc. A variety of gases can be used, depending on the metal reactivity and the nature of the joint. For shielding, this type of welding has advantages in that:

a. It requires low heat input to the material, thereby reducing warpage.

b. It is the easiest method to use for welding in all positions.

c. It produces no slag that might get entrapped in the weld.

The best gas for welding a low-carbon steel appears to be a mixture of 25 percent carbon dioxide and 75 percent argon. The argon in this mixture provides a more stable arc than pure carbon dioxide. One-hundred percent carbon dioxide is not acceptable in electromagnetic shield welding because it produces an erratic arc that produces excessive

spatter, it makes out-of-position welds very difficult, and it is a high-penetration gas that can burn through sheet steel very easily.

A series ER70 wire is recommended. ER70S3 wire should be used for clean materials. For welding in the field, ER70S6 is better on metals that are not perfectly clean. The high silicon content in this latter wire provides a better wetting action along the edge of the weld.

8.3.2.3 **Gas tungsten-arc welding.** Gas tungsten-arc or tungsten inert gas (TIG) welding is used in shielding work, primarily in the shop, for thin materials. A nonconsumable tungsten electrode is used for one electrode of the arc. The arc is shielded with an inert gas, usually argon. The arc heats the metals being welded, as well as the filler metal which is usually fed into the arc by hand. Alternating current (ac) and a 100 percent argon shielding gas are used in most electromagnetic shield welding applications for steel. The arc produces cleaning action during the period that the electrode is positive. This cleaning action removes contaminants and reduces weld porosity.

TIG welding is not commonly used for field applications because it is slower than MIG welding and, therefore, more expensive. However, it has been very successfully used on some shield construction projects. It produces very clean welds with low warpage.

8.3.2.4 **Special considerations in welding stainless steels.** Stainless steels are readily weldable in the field by shielded metal-arc and gas metal-arc welding. Gas tungsten-arc welding can be used for field fabrication, but it is a slow process. Manufacturers' recommendations for welding stainless steel should be followed. These include recommendations on joint designs, preheat temperatures, any associated post-weld treatment, and shielding gas.

These steels have a melting point of about 1400°C (2550F). The coefficient of expansion is about 50 percent greater than that of carbon steels and the thermal conductivity is from one-third to one-half less. Extra care should be taken to provide for expansion and contraction when welding these steels.

During welding the corrosion resistant properties in the weld metal and in the adjacent base metal will be reduced unless one of the following steps is taken to offset this action.

a. Specify the extra low-carbon modification of the type of stainless steel base metal and welding electrode; this is the preferred option.

b. Specify either the columbium (niobium) or titanium modified base metal or welding rod.

c. Specify a solution anneal heat treatment (generally for shop welds only).

The base metal modifications prevent chromium carbides from forming at the grain boundaries. The heat treatment approach causes the chromium carbides to be put back into solution.

Stainless steels should be well protected from atmospheric oxygen and nitrogen during welding to prevent their combining with the hot metal. Post-weld treatments cannot be accomplished reliably in the field and generally are not recommended because the cooling process is difficult to perform.

8.3.3 Shield seam construction. The construction of a welded steel shield is certainly not new technology; many facilities have been built using this technique for protection against HEMP and other rf threats and for TEMPEST controls. Some projects have gone well; others have been very bad experiences. The keys to a successful program appear to be designs for straightforward construction, designs that allow modification, specifications with unambiguous performance requirements and quality control provisions, and well-qualified welders and quality control inspectors. It is important that the Government, as well as the contractor, be represented in design reviews and during critical construction phases by personnel who are knowledgeable and experienced in HEMP hardening. Areas requiring particularly close attention include:

a. Floor shield design: Buckling of the floor shield due to direct solar heating during construction and to the heat applied during the seam welding process has been the single greatest construction difficulty in many projects.

b. Floor shields imbedded between the concrete subfloor and a wear slab should be avoided, if possible. If this configuration is necessary, it must be carefully designed and fabricated to minimize corrosion and other failures due to the difficulty and expense of life-cycle HM/HS.

c. Corner seams: The designer should carefully detail all corner seams, particularly where three shield surfaces join, and ensure that the required access is available to complete welds and to allow HM/HS at these locations. Whenever possible, a one-meter wide clear space should be provided to permit complete visual inspection of shield surfaces from both sides.

d. In-progress weld testing: An active in-progress weld testing program is needed during shield assembly to avoid systematic procedural mistakes that will lead to costly repairs later (see section 16).

Three basic options for joining and electrical bonding at the seams between adjacent steel sheets, as identified in table VI, are discussed (reference 8–12).

8.3.3.1 **Sheet metal pan.** Figure 19 shows the installation of the shield using a sheet metal pan, formed by cutting and bending the sheet stock and welding at the corners. This technique has several advantages:

a. The square flange weld at the seam is very easy to make and inspect.

b. The ability to clamp adjacent pans together prior to welding will simplify the initial shield layout.

c. The seam can also be used as an expansion joint.

d. Because of the rigidity of the pan, the problem of buckling may be reduced.

Principal disadvantages of the pan method are the amount and cost of required shop fabrication and reduced density for transportation. After cutting and bending to form the pan, the corner welds must be carefully made and inspected in the shop; repairs to the comer welds are more difficult to perform after the pan has been installed. Because hydraulic brakes larger than 3.7 m (12 ft) to perform the bends are uncommon, competition on materials purchase may also be limited for sheets longer than this dimension.

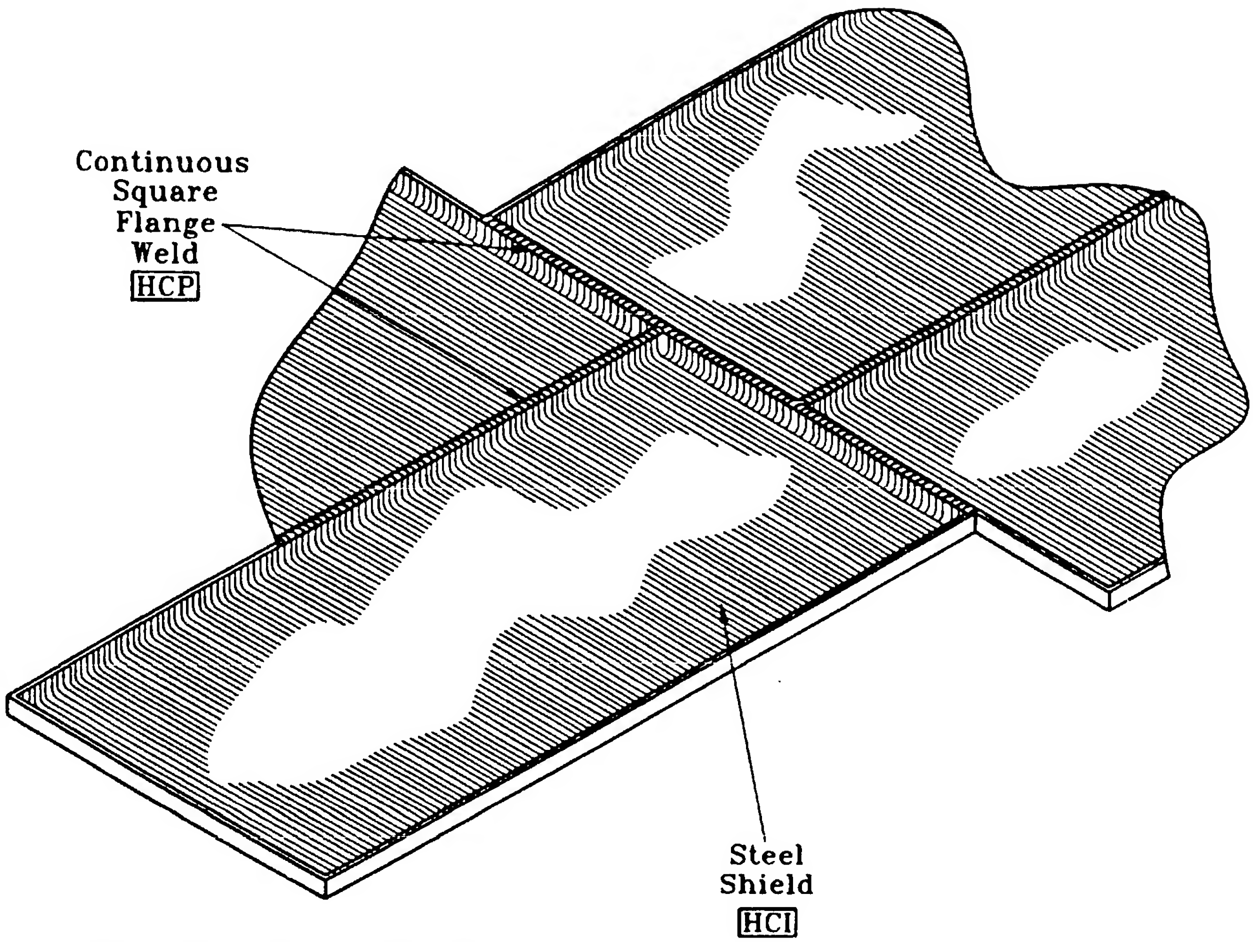
An offset between adjoining pans, as seen in figure 19, may be used to minimize the tendency to buckle as the welding is performed. Experience is required to evaluate the tradeoffs between this advantage and the increased complexity of shield layout that it creates.

A typical floor pan shield design is shown in figure 20. The HEMP shield is installed above the concrete subfloor and below the raised floor. The volume under the raised floor is used as an air supply plenum, and interconnecting cables between equipment racks may be run in this area. MIL-HDBK-419 (reference 8-13) and section 13 of this handbook discuss the grounding of the raised floor.

Figure 21 shows a floor shield pan joint in somewhat greater detail. The bend is made with a radius of approximately 2.5 cm (1 in), which permits the joint slight freedom of expansion and contraction motion. The height of the lip at the edges of the sheet is usually about 5.1 cm (2 in). This drawing also illustrates a concrete wear slab, although the use of wear slabs above the floor shield is discouraged. If a wear slab is required, however, it should be 12.7–15.2 cm (5-6 in) in thickness. Thinner slabs may easily crack under load at the shield seams.

TABLE VI. **Shield seam construction methods.**

Basic Techniques	Variations	Shop Fabrication Required	Potential for Buckling	Anchored to Subfloor	Advantages/ Disadvantages
Pan technique	Not applicable	Cutting, bending, and welding	Low	Not required	Welds easy to perform and inspect; simplifies shield layout; materials cost highest; sheet size may be limited
Butt-welded sheets	Basic	None	Greatest	Not required	Largest available sheets can be used; more difficult welds
	With plug welds	Drilling	Low	Yes	Additional plug welds and weld tests
	With backing structure	None	Low	Yes	Welds are simplified but two beads may be required
Lap-welded sheets	Basic	Cutting	Moderate	Not required	Welds are easier than butt welds; largest available sheets can be used; susceptible to crevice corrosion
	With plug welds	Cutting and drilling	Low	Yes	Additional plug welds and weld tests
	Preshaped sheets	Bending	Low	Not required	No gaps under plates; provides expansion; material costs high; sheet size may be limited



NOTE: Also see figures 20 and 21

FIGURE 19. Pan-welded shield seam.

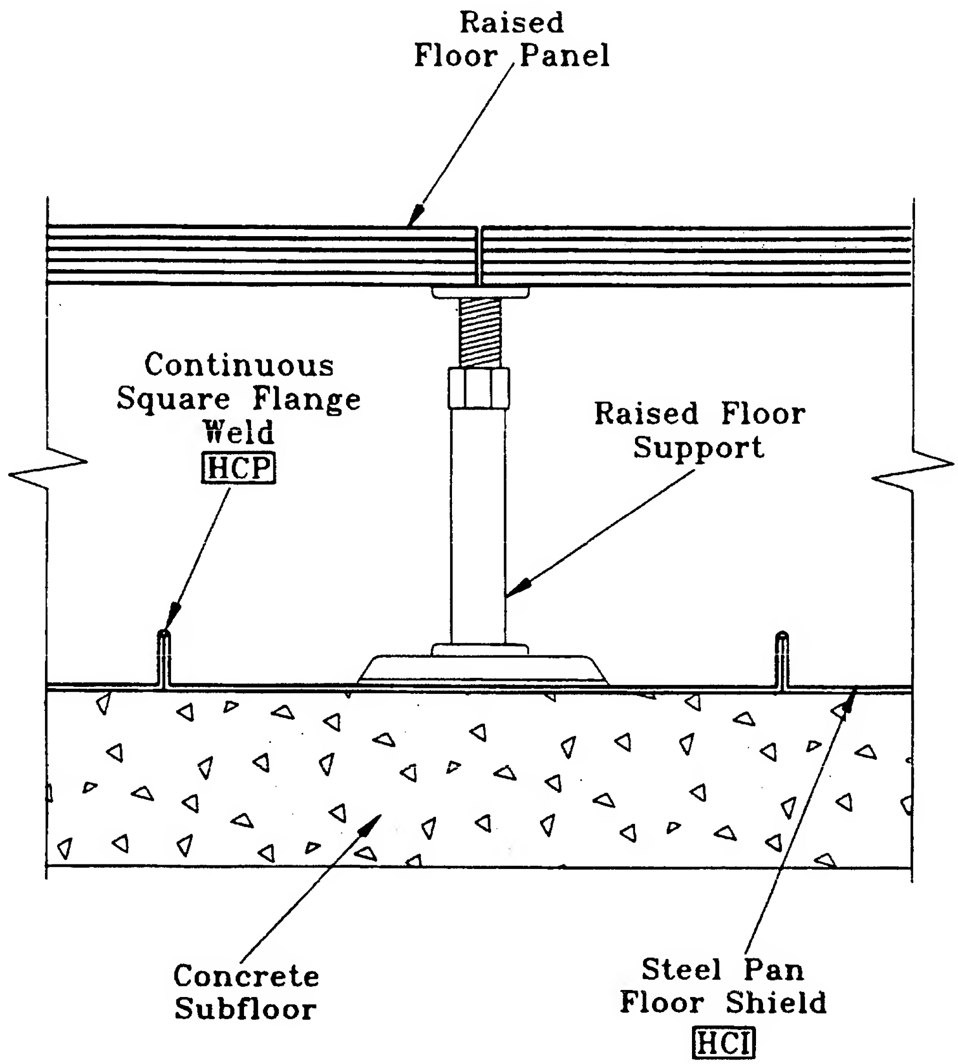


FIGURE 20. **Pan-welded floor shield under raised floor.**

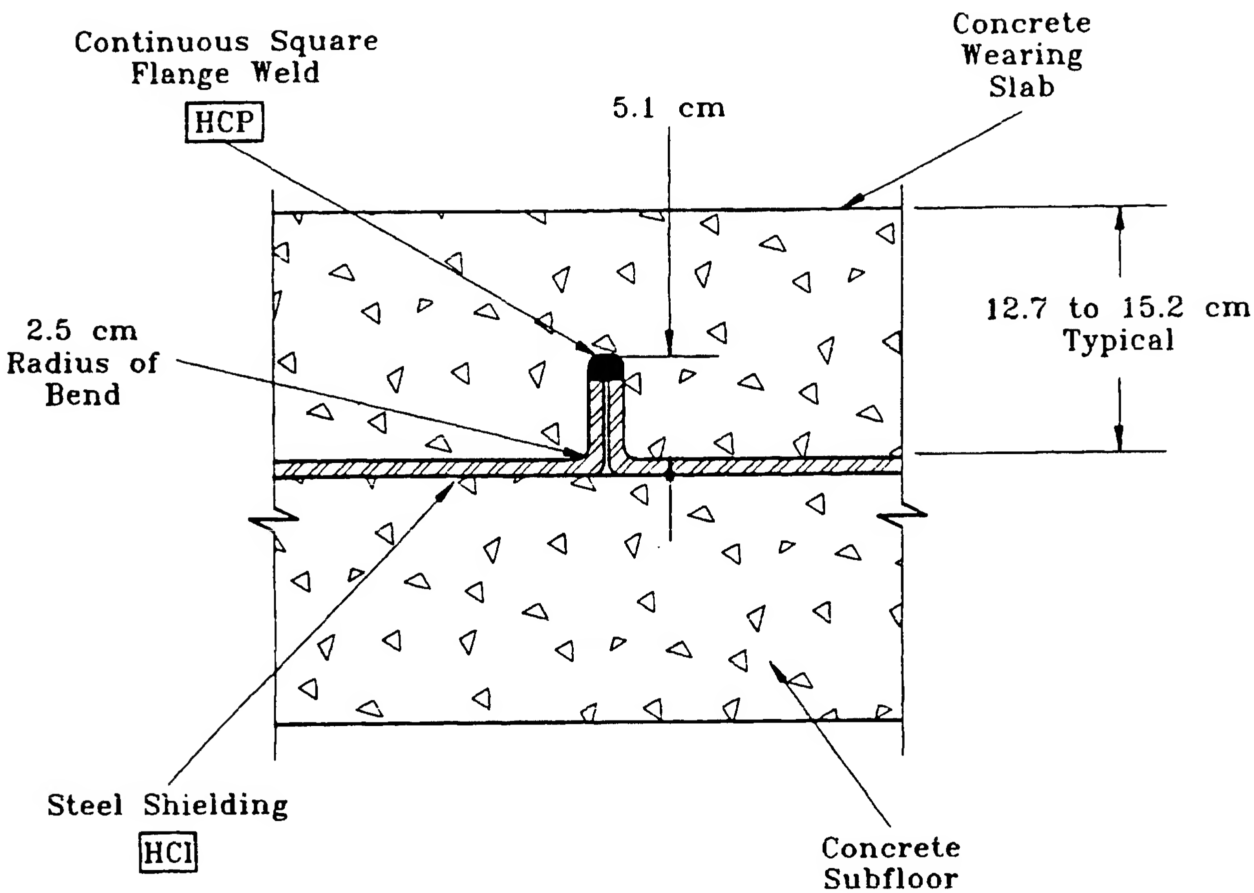


FIGURE 21. **Floor shield pan joint with wear slab.**

On walls, the pans may face inward or outward. Access to perform the quality assurance testing and future periodic inspections of the welds is the primary factor in this determination by the designer. Inward is probably the most efficient in concrete and concrete masonry buildings. If the pans in the ceiling face upwards, overhead welds can be avoided by use of assembly techniques where the shield ceiling is assembled at floor level, then hoisted and secured in place.

8.3.3.2 **Butt-welded seams.** A basic butt-welding approach is illustrated in figure 22. The technique can use rectangular sheet stock in the largest available size and requires no shop fabrication, leading to the lowest material costs. This method has exhibited the most severe buckling problems during shield assembly, particularly when insufficient plate spacing is provided for thermal expansion in the initial shield layout. The buckling tendency can be reduced or eliminated with plug or puddle welds to underlying

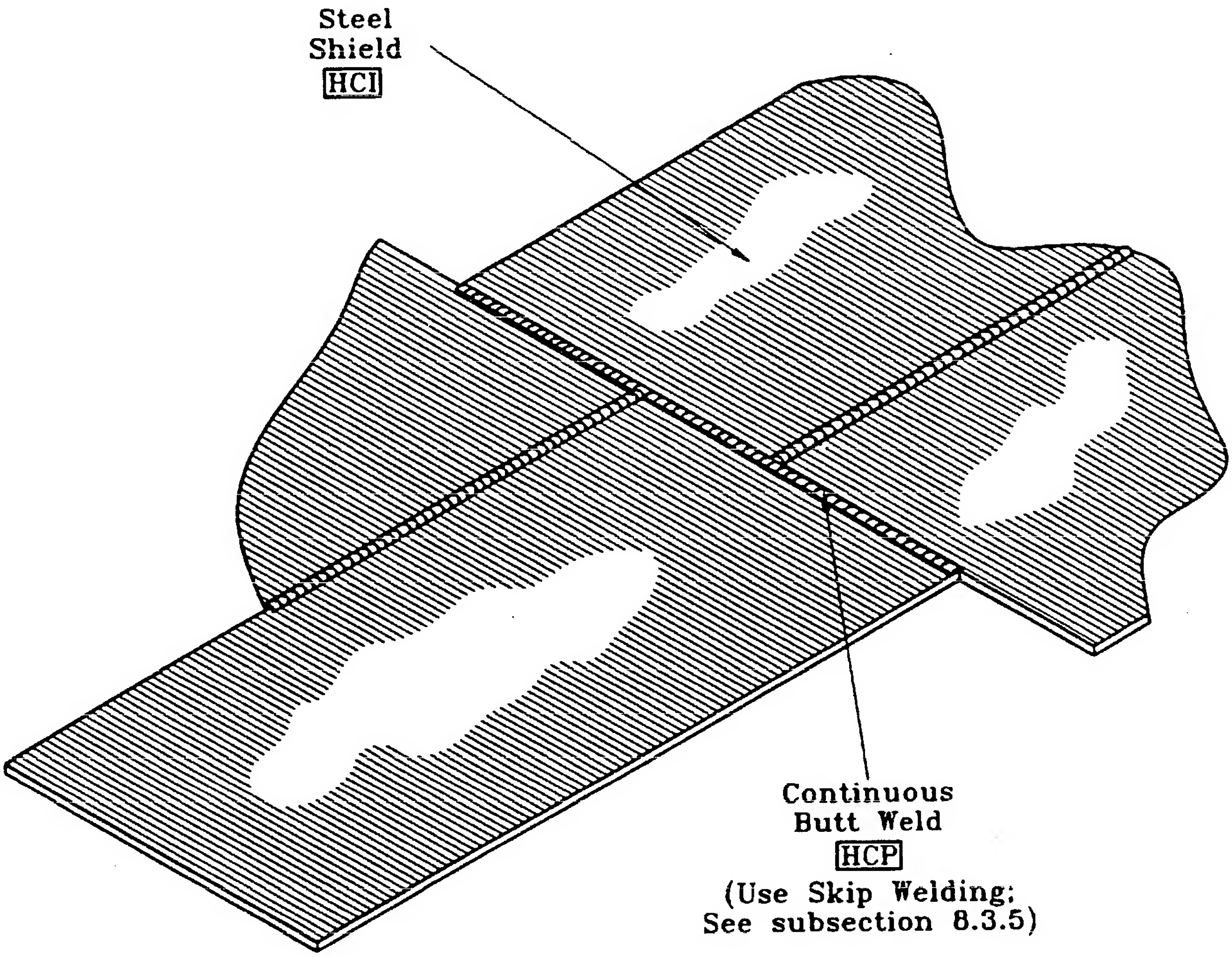


FIGURE 22. **Butt-welded shield seam.**

furring strips (figure 23), a structural steel backing material (figure 24), or a combination of these measures. The costs associated with these variations will at least partially offset the price advantage of the basic method.

8.3.3.3 **Lap-welded seams.** Figure 25 illustrates the basic lap-welded seam option. Lap welding procedures are somewhat less difficult than butt welds. A disadvantage is the susceptibility to crevice corrosion if water seeps between the metal surfaces in the overlapped area. Again, the largest available sheets can be employed, and rather loose dimensional tolerances are acceptable. Floor buckling in post projects constructed with lap-welded seams has been moderate. The variation involving plug welds to an anchored furring strip can also be applied to this approach.

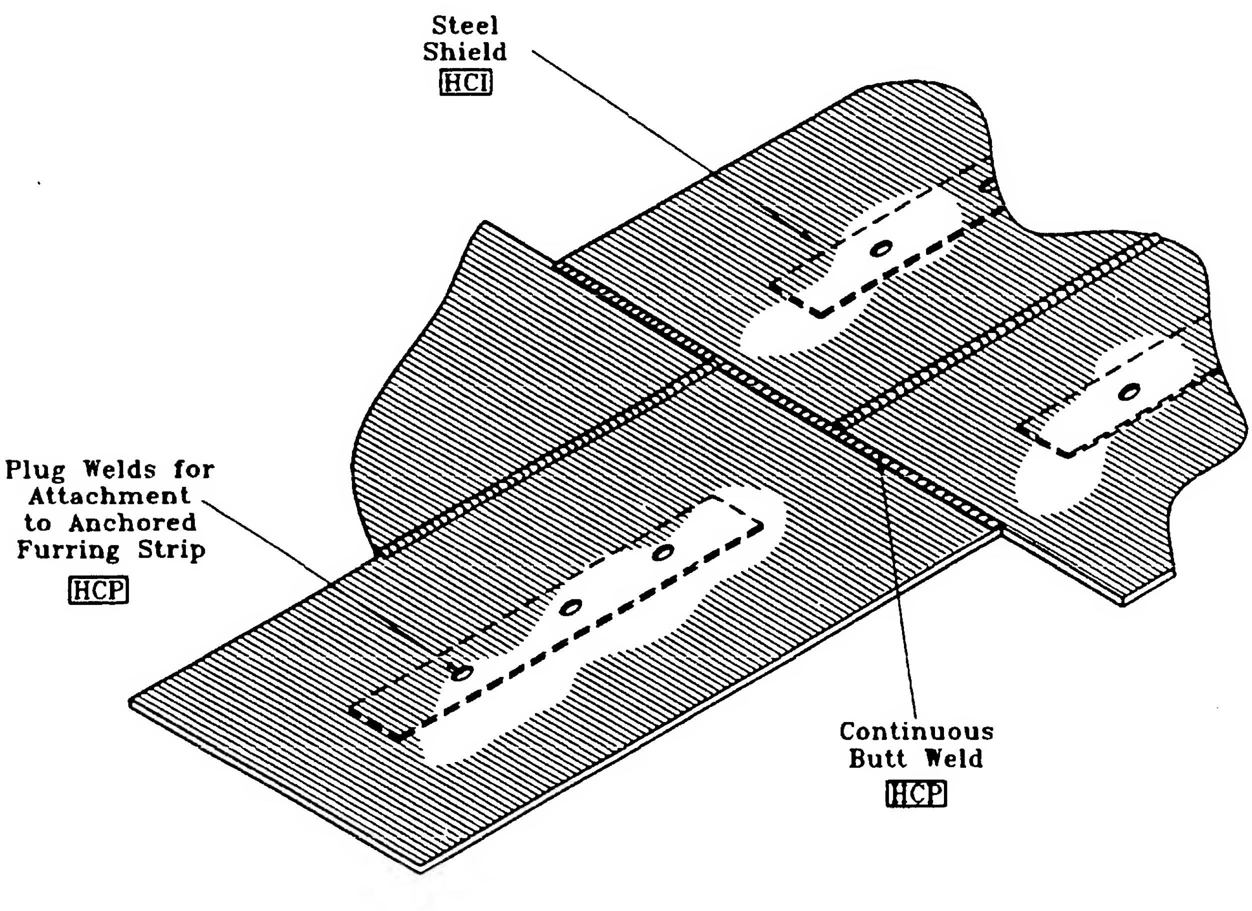


FIGURE 23. **Butt-welded shield seam with plug welds.**

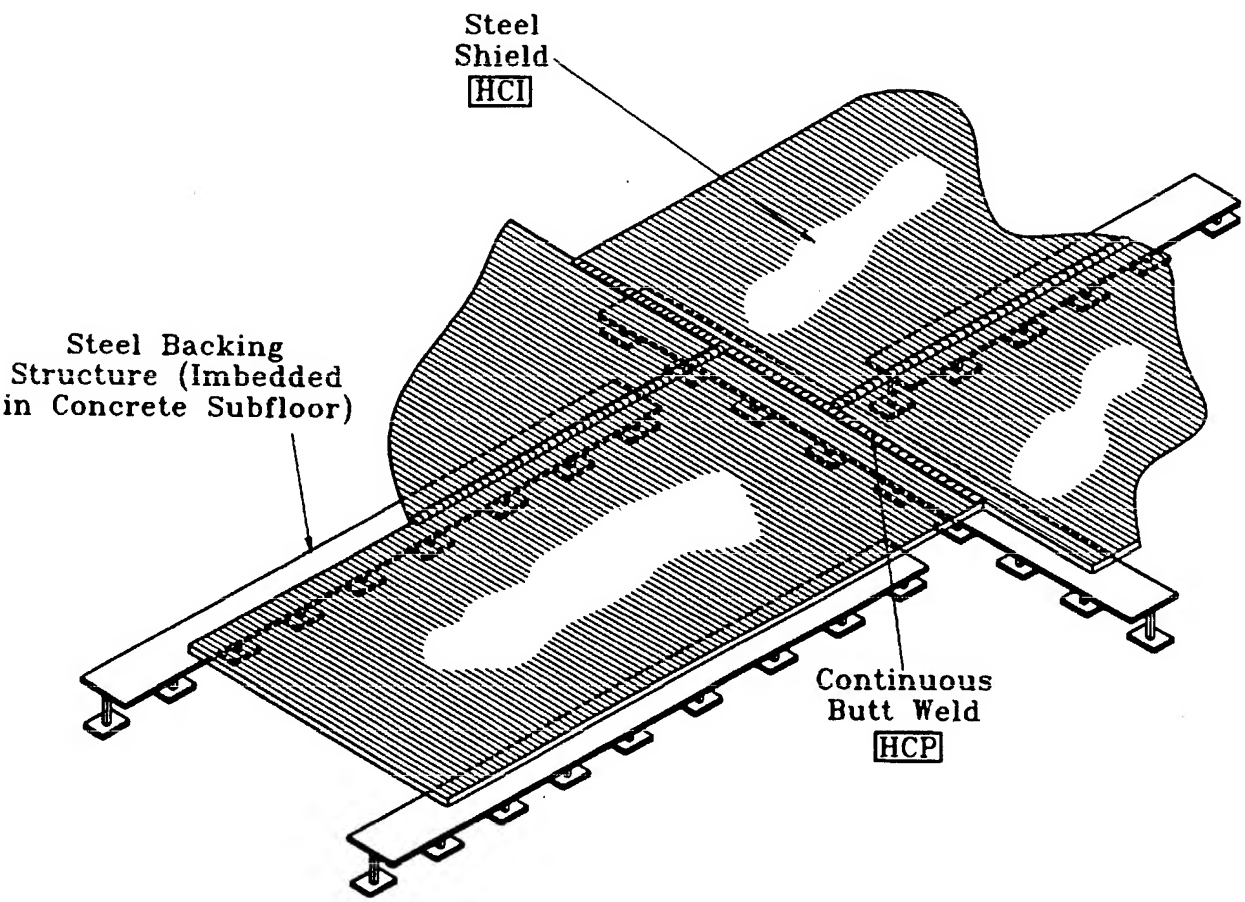


FIGURE 24. Butt-welded shield seam with steel backing.

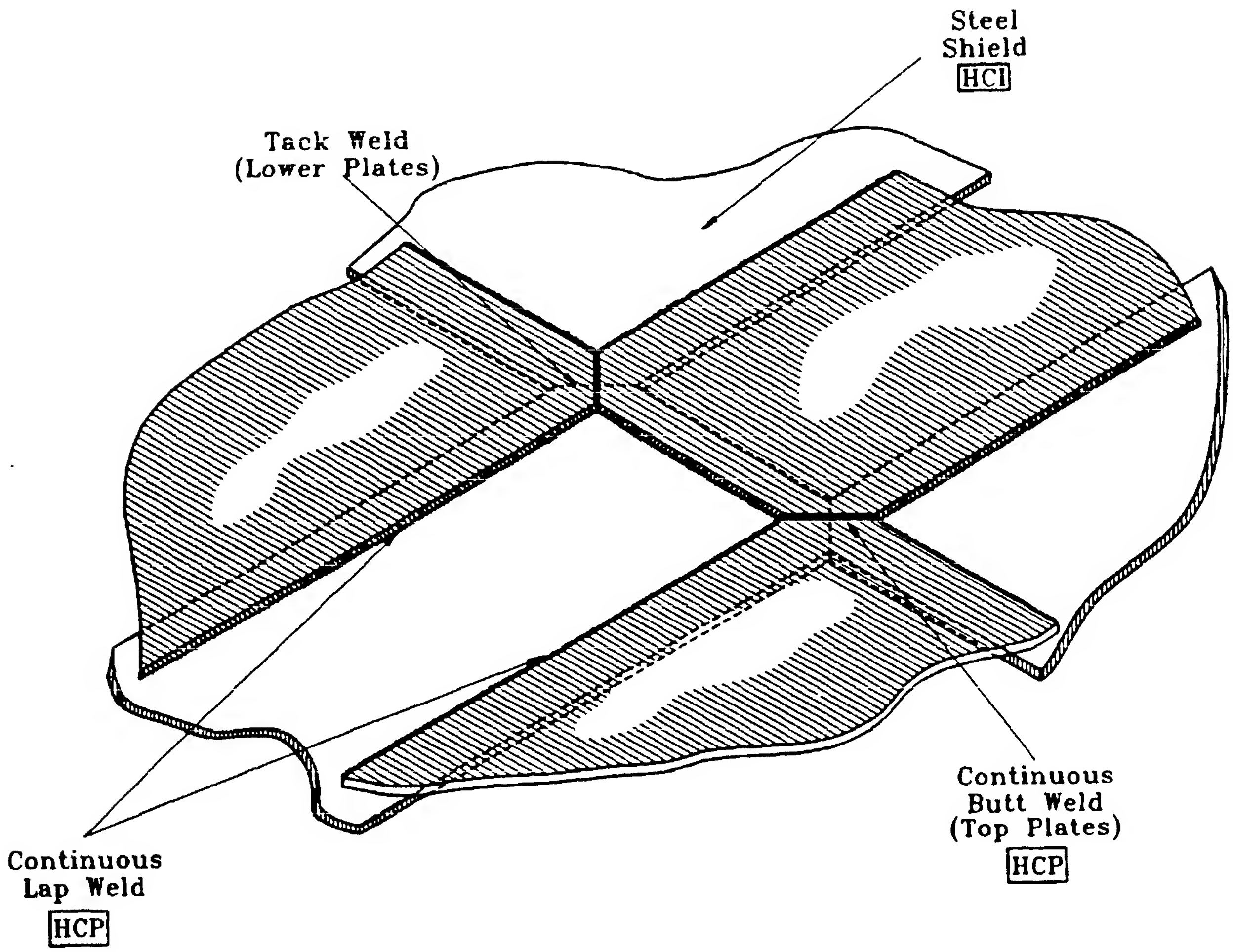
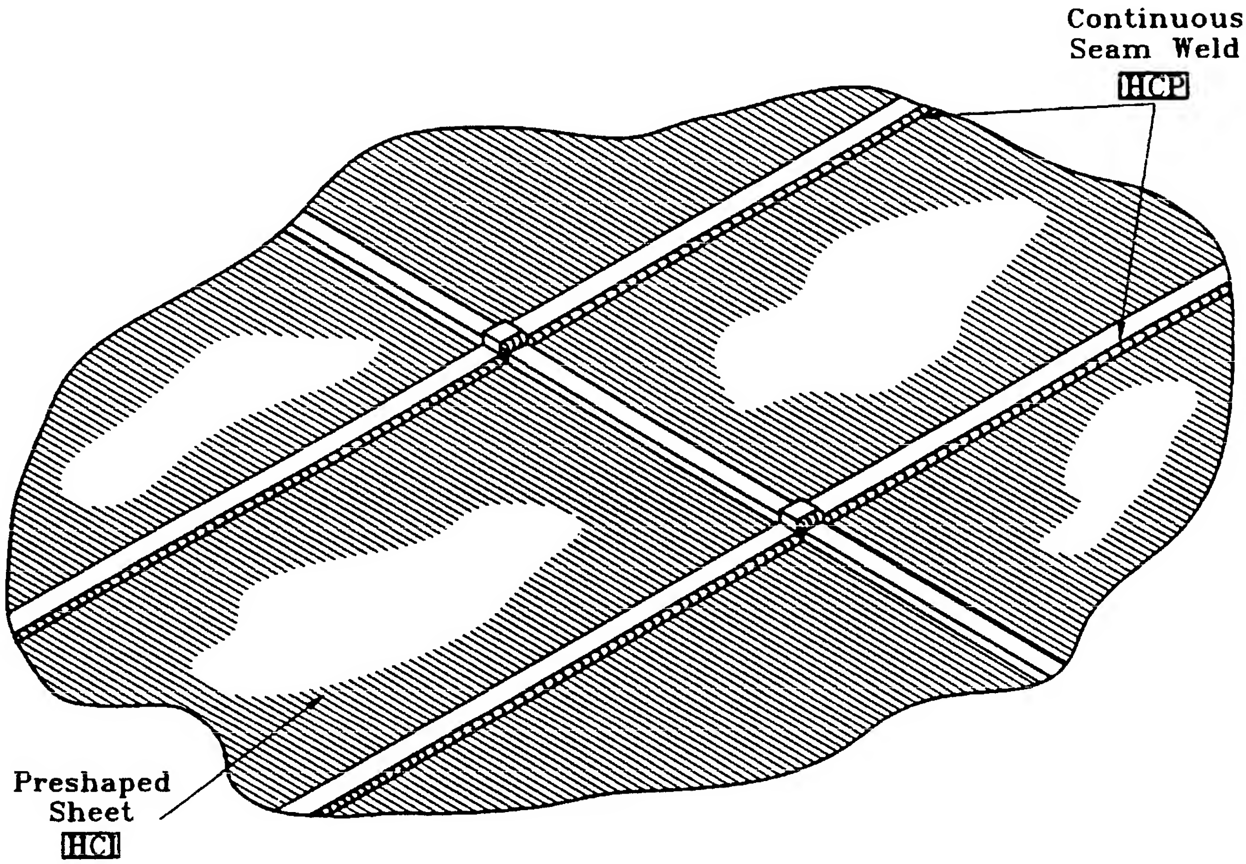


FIGURE 25. Basic lap-welded shield seam.

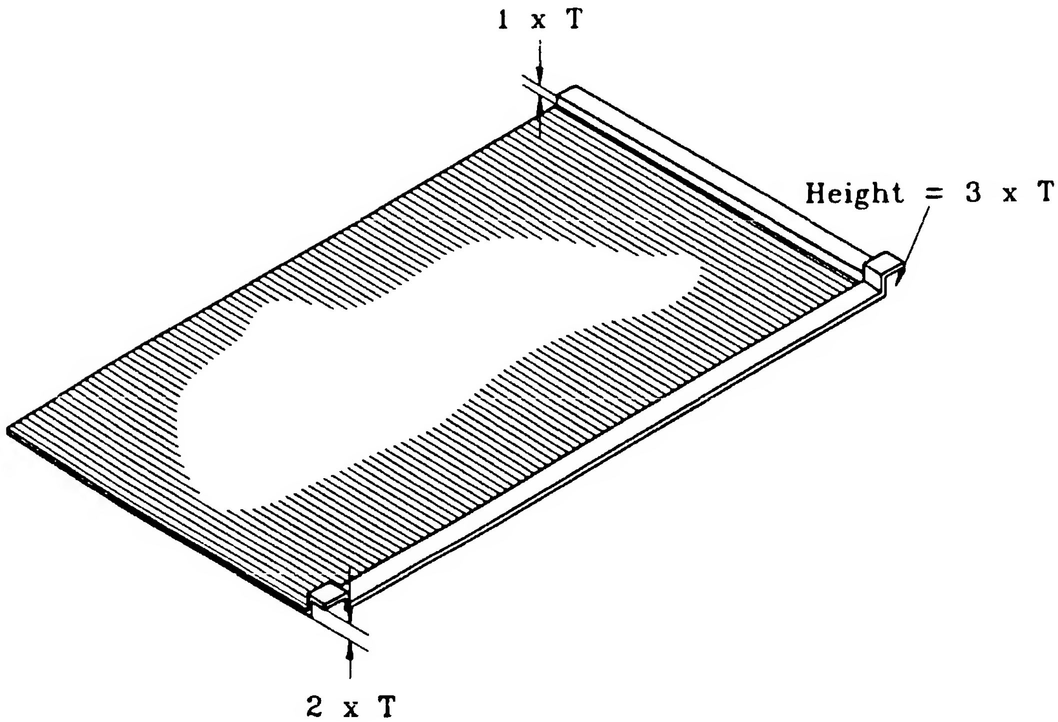
Lapping of the sheets, however, will result in air gaps under the plate, unless the level of the structural subfloor is terraced to conform. This leads to a concern that heavy machinery rolling across the floor will cause cracks in the seam welds. The problem can be alleviated by the use of "preshaped" sheets, bent to accommodate the overlap while allowing the bulk of the plate to lie flat on the subfloor.

Figure 26a illustrates a HEMP floor shield assembled using lapped, preshaped sheets. A single sheet is shown in figure 26b, with the vertical dimension exaggerated. Each sheet is bent along two sides and in two corners to smoothly overlap the adjacent panels by approximately 5.1 cm (2 in). One sheet thickness must fit under the sides, while two or three thicknesses must fit under the corners as indicated. The sheets can be anchored to

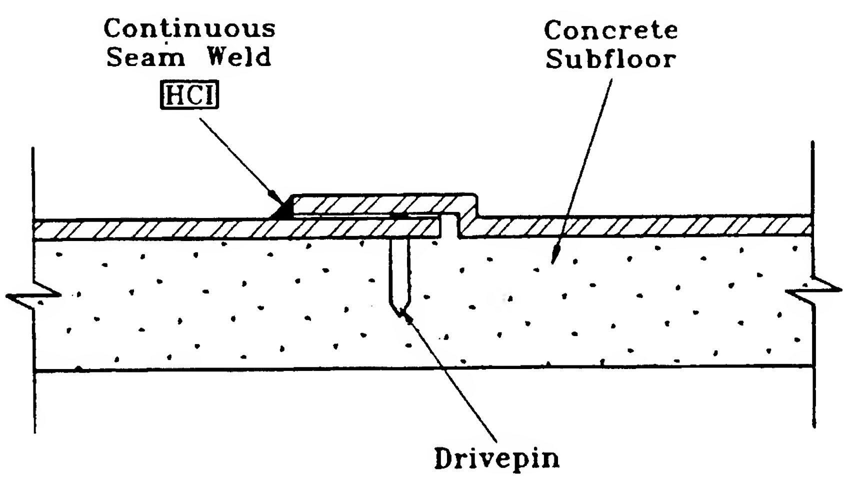


a. Assembly isometric view.

FIGURE 26. Lap-welded preshaped sheets.



b. **Preshaped sheet.**



c. **Cross section of overlap area.**

FIGURE 26. Lap-welded preshaped sheets (continued).

the subfloor in the overlap area, as shown in figure 26c. It is not necessary to weld around the anchor heads, since they are topologically outside the electromagnetic barrier.

8.3.3.4 Comer seams. Figure 27 shows a suggested method for joining the wall and floor shields. The corner is formed by a steel angle, probably of much greater thickness but not less than the gauge of the sheet material. If the pan assembly technique is employed, the edge pieces are unbent at the corner and a continuous lap-welded seam is made between the two pieces. The relative positions between the angle and sheet (inside vs. outside) are not critical and should be chosen for welding convenience. The overlap at the corner seam should be about 2.5 cm (1 in) or greater.

Regularly placed metal studs, which may be tack welded to the shield, provide shield support and rigidity. The studs may also be used as attachment points for the interior finish work and wall-mounted panels. The interior finish configuration is not a subject for this handbook, except to note that shield inspectability must be preserved.

A typical wall/ceiling corner, figure 28, is formed by the same technique. Relative positions of the angle and plate are again arbitrary. Overhead metal joists may be placed regularly and tack welded to the ceiling shield to add rigidity and provide strength for supporting a suspended ceiling and light fixtures.

Wall-wall corners are formed in an identical manner. Where two walls and the floor (or ceiling) meet, three intersecting angles must be fitted together. For these complex intersection fittings, shop fabrication should be considered.

8.3.4 The shield/POE interface. Provisions must be made in the shield for electrical bonding of the protective elements to be used on penetrations and apertures. For large apertures such as doors and ventilation panels, this means providing a surface of the shield around the entire aperture perimeter to which the aperture treatment will be welded. Housings used for filters or nonlinear protection devices must be circumferentially welded to the shield, since the shield will provide the path for current shunted by these devices. Metal penetrations that can be grounded, such as pipes, waveguides, and cable conduits will be circumferentially welded at the outer surface of the shield. Many such connections will be made at the PEA; this area of the shield must be readily accessible for inspection during system operations.

Metal shield door frames, flanges on ventilation waveguide-below-cutoff panels and filter/ESA assemblies, pipes, conduits, and other penetration protection devices are to be bonded to the shield by welding or brazing. Metals used to construct the penetration treatments should be galvanically compatible with the shield material. If dissimilar metals

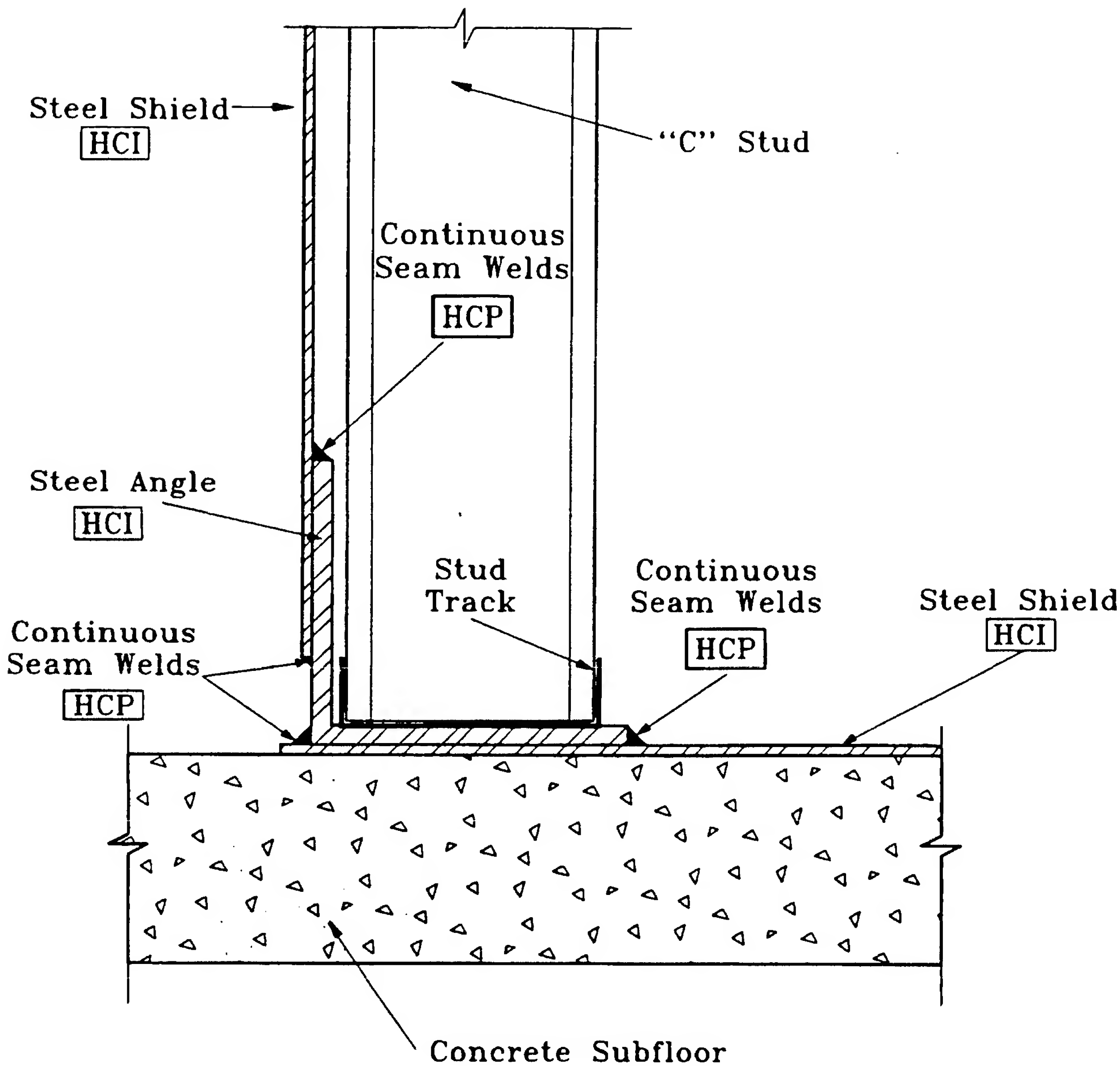


FIGURE 27. Wall/floor shield joint.

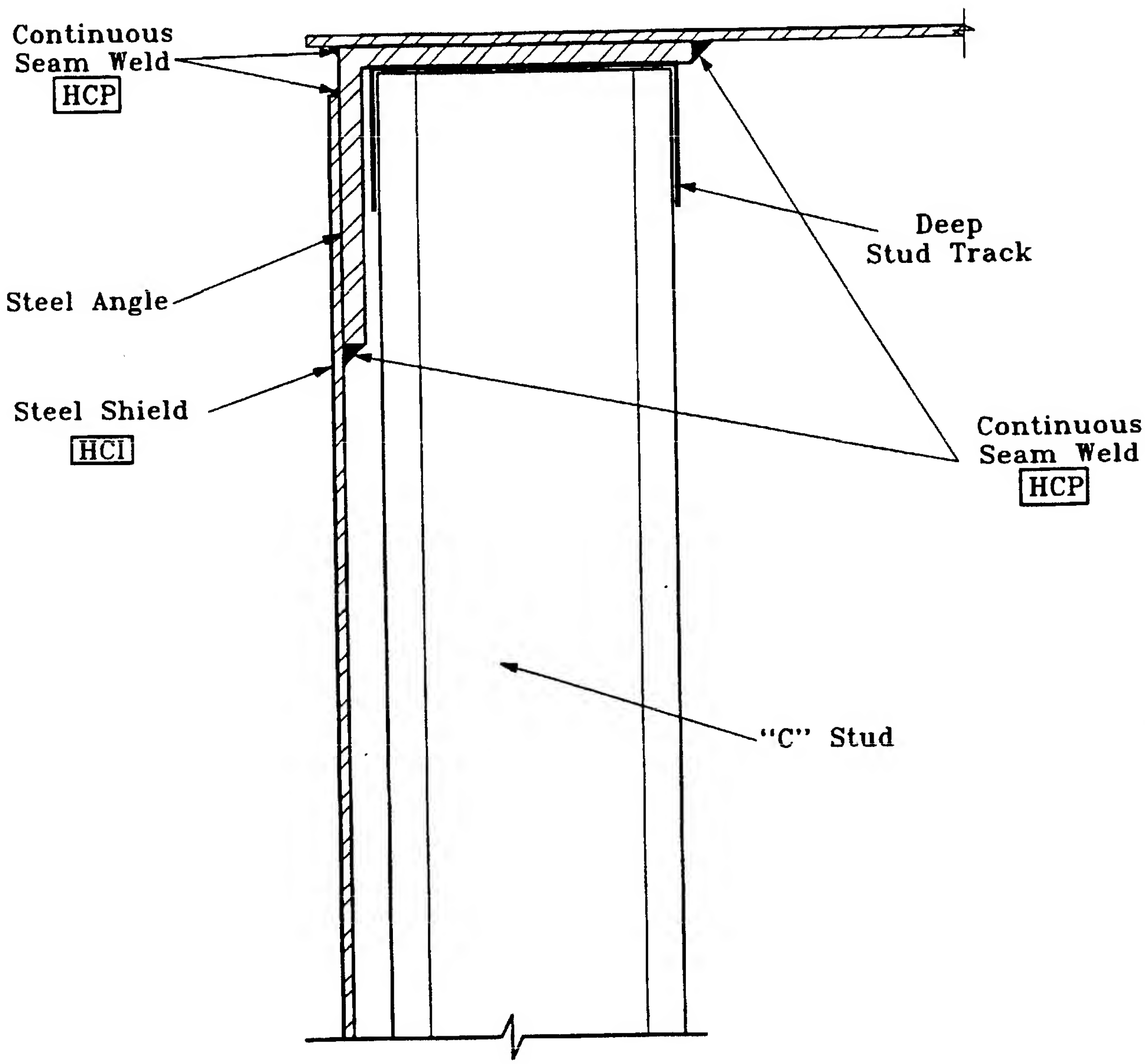


FIGURE 28. Wall/ceiling shield joint.

are employed, they should be adjacent members of the electromotive series, or special conductive anti-corrosion materials must be applied (see section IS). Additional information on the design of POE protective devices is contained in sections 9 through 12.

8.3.5 Metal warpage and buckling. On the job site, the biggest welding fabrication problems that occur are metal warpage and buckling. These problems can result from solar heating of the materials prior to welding, and local temperatures can reach 1400°C (2550°F) from the heat input during welding. Since steel expands during heating ($\Delta \ell = 6.5 \times 10^{-6} \ell \Delta T$), rigidly connecting materials that are at different temperatures will build thermally induced stresses into the material. Buckling and warpage occur as the materials move to reduce these stresses.

Many thermal problems can be avoided by preventing shield materials from being exposed to the sun. The outer building shell or a temporary cover should be erected before shield layout and assembly. The enclosure should be heated to a reasonable working temperature during winter weather conditions.

Welding is best done when the materials are at nearly uniform temperature. Sheets should be set in position and allowed to approach the same temperature before the seams are welded. Where possible, adequate sag should be allowed to assure that daily temperature cycling does not break or pull out the mechanical fasteners or welds that hold the shield to items such as the supporting studs, beams, and roof decking.

The welding process itself is responsible for the most severe warpage problems. Since the welding temperature is very high, the material near the arc and the cooling bead is expanded. When this material contracts, distortion is obtained by:

a. Transverse shrinkage that occurs perpendicular to the weld line

b. Longitudinal shrinkage that occurs parallel to the weld line

c. Angular change that consists of rotation around the weld line

Figure 29 shows an example of transverse shrinkage distortion and rotation. The distortion can be reduced by reducing the total weight of the weld material, which decreases the total heat input to the weld.

Longitudinal shrinkage is more difficult to anticipate, because the effect depends upon the thickness of materials, the welding speed, and the total heat input to the material. Since the materials near the weld are heated, they try to expand but are constrained by the cooler materials further away from the weld. This will tend to cause the sheets to

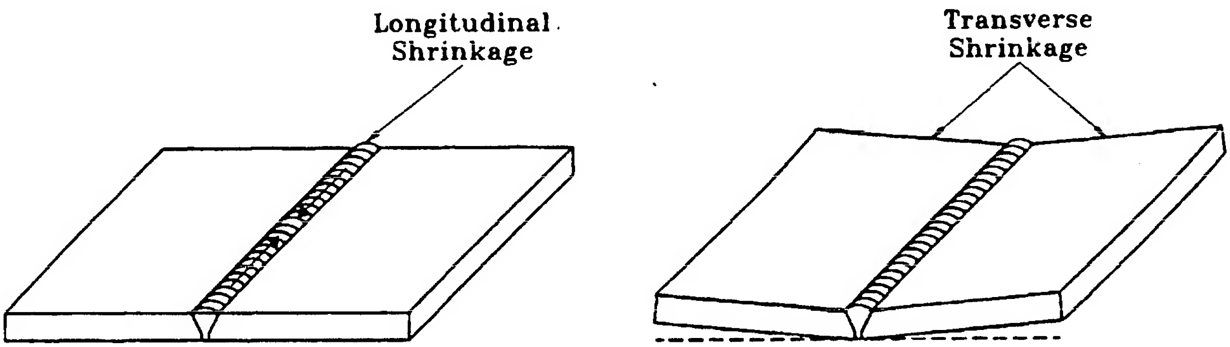


FIGURE 29. Longitudinal and transverse shrinkage.

rotate away from the weld line if the weld is fast, or to rotate into the weld line in slow welds. In severe cases, the base material may crack along the weld line.

Methods to control weld-induced warpage in the field include preheating the steel, physical restraint of the sheets, and use of a skip welding or back stick welding technique (figure 30) to limit the temperature excursion of the metal in the weld area. When specified in the drawings, power-activated fasteners are employed to anchor the floor shield sheets to the concrete foundation. Tack welds are made on the first pass of the skip welding process to attach the sheets to each other (or to steel strips, studs, or beams used as a backing structure) at about 30-cm (1-ft) intervals. On the second pass, an 8-cm to 10-cm bead is attached to each tack along the length of the seam. The bead length is extended by an additional 10-12 cm on the third pass, and the seam weld is completed on the fourth pass. In no case should the bead length on a single pass extend about 15 cm, because the residual longitudinal stress that causes the distortion increases rapidly for greater lengths (figure 31).

The welders and quality control inspectors should be aware that a potentially major problem with skip welding is that a seam with many discontinuities can be produced. To avoid thousands of small leaks in a facility, welders must ensure that the metal is remelted at each end of each short bead, while still ensuring that the temperature remains low enough to preclude severe warping.

8.3.6 Copper shields. A copper HEMP shield is inherently much less durable than a steel shield and therefore should be used only when steel is not a practical option. This situation may occur in a retrofit hardening project, where it is necessary to form

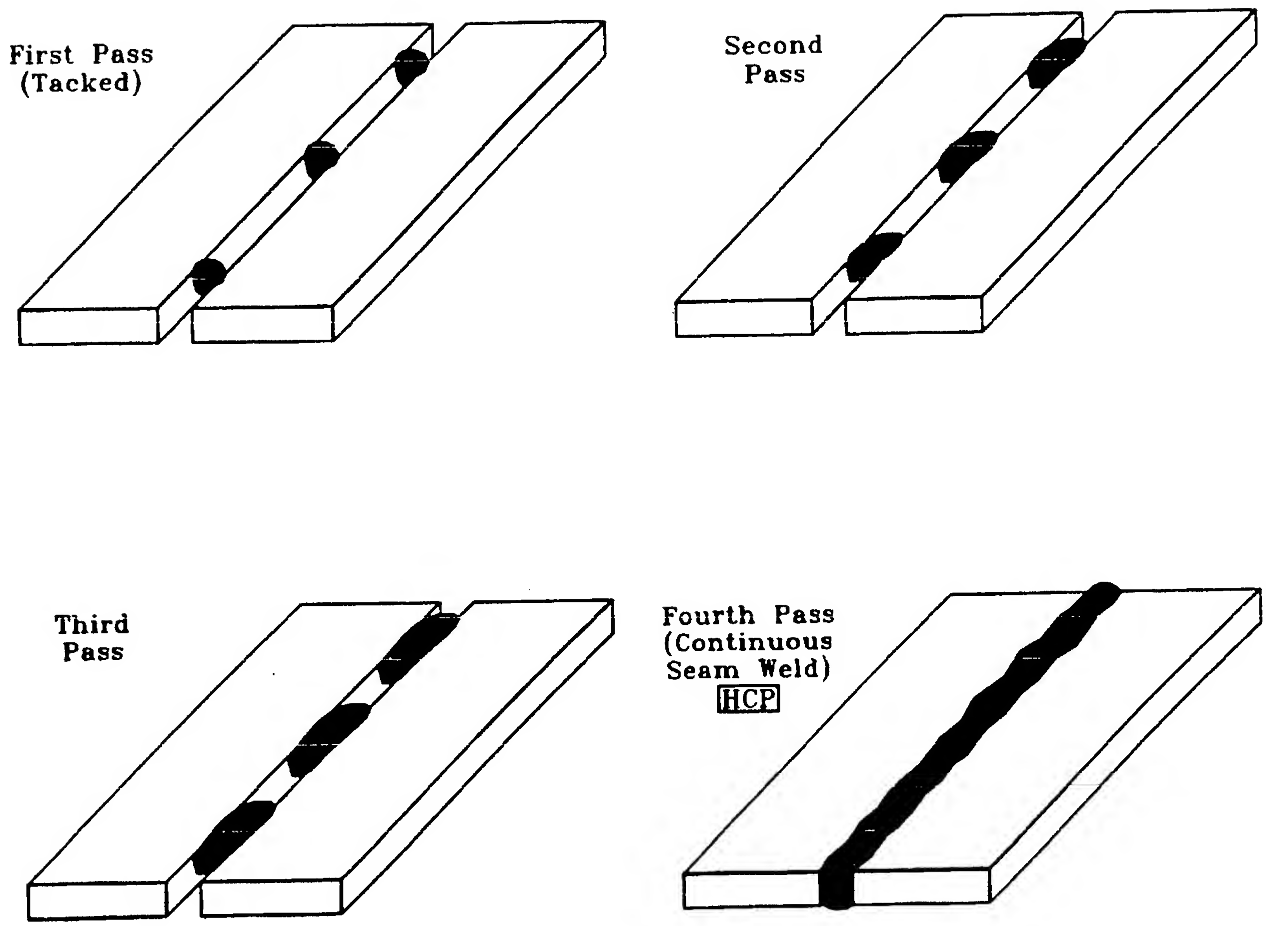


FIGURE 30. Skip welding techiques.

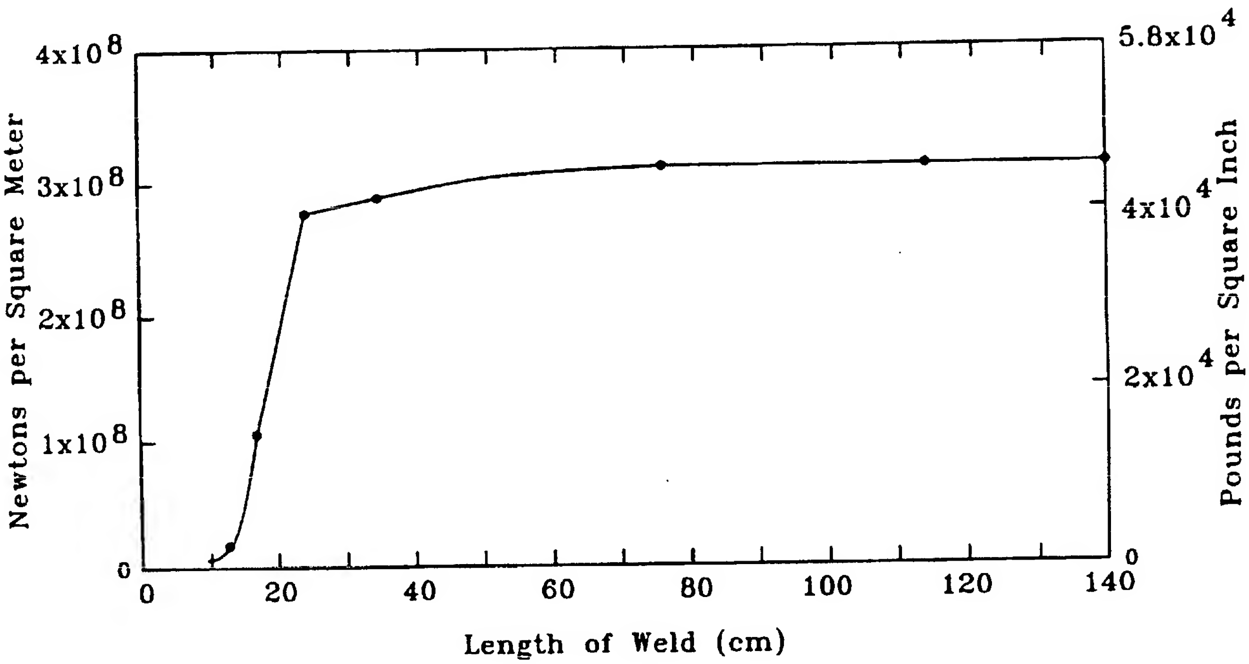


FIGURE 31. Longitudinal stress vs. bead length.

a building-level shield around a complex arrangement of existing walls and structural elements. Copper may also be most practical for shielding modifications to equipment racks and drawers.

When a copper shield is necessary, essentially pure copper with less than 0.7 percent noncopper content is recommended. The sheet thickness should be between 0.27 mm (0.01 in or 8 oz) and 1.1 mm (0.04 in or 32 oz). Sheets of this thickness are generally available in widths up to 91 cm (3 ft) and lengths to 3 m (10 ft).

Adjacent sheets should be overlapped by approximately 2.5 cm (1 in) and joined by torch brazing, using a copper-phosphorous or silver-copper alloy filler and flux material. Since these materials will not adhere to a contaminated surface, the base metal must be cleaned to remove all dirt, grease, scale, corrosion) and other contaminants.

The copper sheet will conform to the backing surface, so that buckling is not a problem.

The copper shield has virtually no structural rigidity and very low puncture resistance. Thus, a frame and protective covering such as plywood must be provided separately.

Copper is corrosion-resistant in contact with air, water, and even moist soil. In contact with other common metals, copper is almost always cathodic and immune to galvanic attack. Such joints between dissimilar metals must be protected as discussed in section 15.

8.4 References.

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9. ARCHITECTURAL POINTS-OF-ENTRY

9.1 Basic principles.

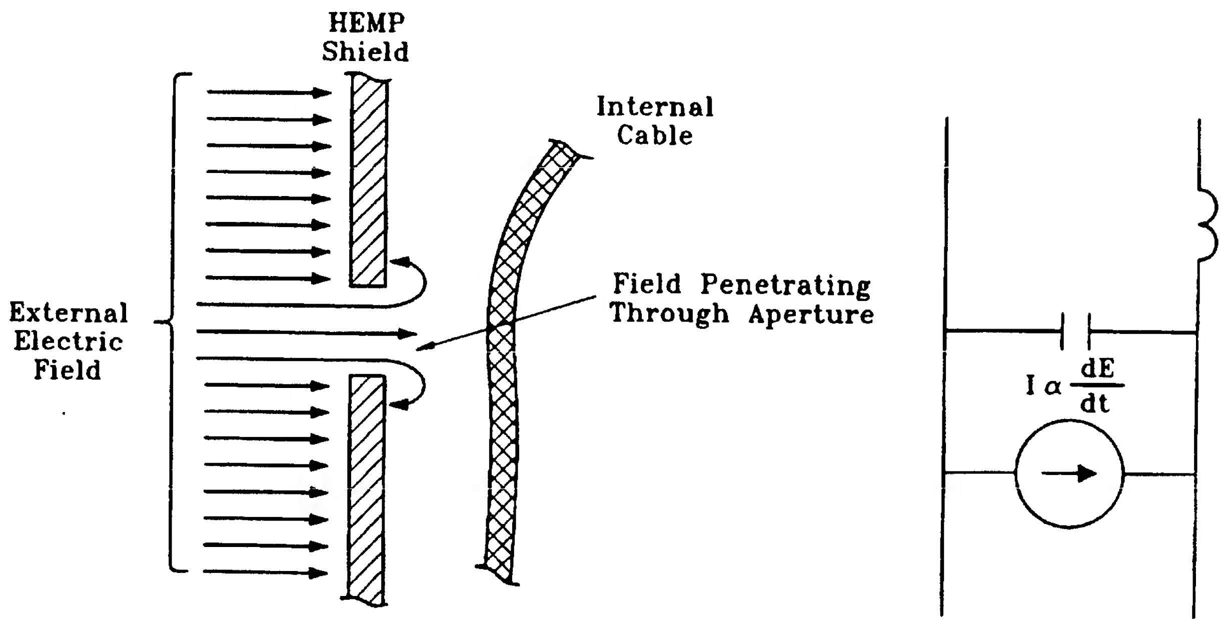
9.1.1 Introduction. Architectural points-of-entry are openings in the HEMP shield that allow for personnel entry and exit and for movement of equipment into and out of the protected volume. Windows should not be provided in a high-quality electromagnetic barrier, and the treatment of a window aperture will not be covered in this handbook. Architectural POEs are the largest apertures in the barrier. Therefore, they have the greatest potential for electromagnetic field leakage unless proper protection is implemented and maintained.

HEMP hardening at architectural POEs is provided with waveguide-below-cutoff techniques, electromagnetic closure, or a combination of waveguides and closure. Basic principles of aperture leakage and the associated protective approaches are discussed in 9.1.2 through 9.1.4. Subsection 9.2 reproduces the requirements in MIL-STD-188-125 (reference 9-1) that are applicable to architectural POEs. Subsection 9.3 then provides design and construction information to assist the architect-engineer and builder in meeting the MIL-STD-188-125 requirements.

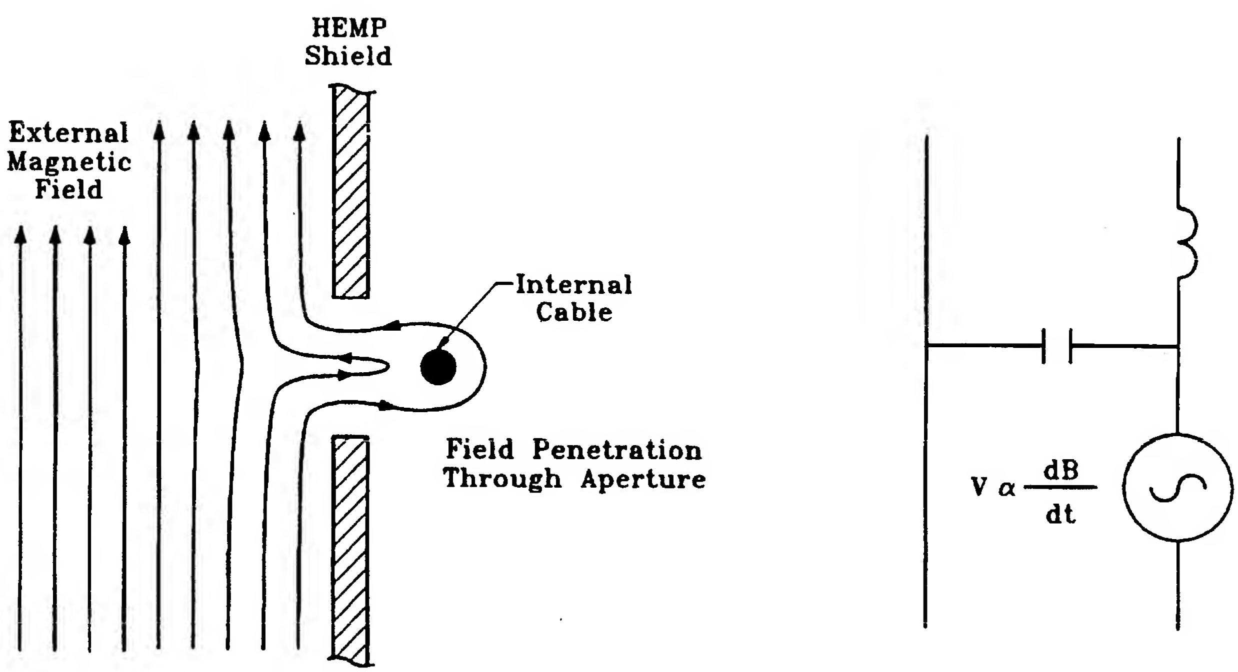
9.1.2 Aperture points-of-entry. Aperture points-of-entry are intentional or inadvertent holes, cracks, openings, or other discontinuities in the HEMP shield. The personnel entryways and equipment accesses addressed in this section of the handbook are examples of intentionally installed aperture POEs. Others include the piping and ventilation penetrations (section 10), which permit fluid flows through the barrier surface, and waveguide-below-cutoff stubs for penetrating fiber optic cables (section 12). Inadvertent aperture POEs occur when shield seams and joints are incompletely closed and when holes are created due to shield corrosion or physical damage.

Ground-based facilities frequently have several large openings, such as personnel entries and cargo doors. Treatment of large aperture POEs such as these is particularly important, because unprotected aperture POEs permit the HEMP to interact with internal wiring. An unprotected aperture POE will allow external HEMP fields to leak into the protected volume, where they can interact to produce potentially disruptive transients (figure 32). The maximum short-circuit current I_{sc} and open circuit voltage V_{oc} induced on a nearby internal cable by leakage through an electrically small hole of radius a (reference 9-2), for example, are approximated by the following coupling equations:

$$I_{sc} \approx \pi \epsilon_0 a^2 \frac{\partial E(r)}{\partial t} \qquad\qquad V_{oc} \approx 4\mu_0 a^2 \frac{\partial B(r)}{\partial t} \tag{8}$$



a. Electric field.



b. Magnetic field.

FIGURE 32. Electromagnetic penetration of small apertures.

where

a	=	radius of hole (m)
r	=	distance from the aperture to the conductor
ϵ_0	=	permittivity of free space = 8.854×10^{-12} F/m
μ_o	=	permeability of free space = $4\pi \times 10^{-7}$ H/m
c	=	speed of light = 3×10^{8} m/s
E	=	incident electric field (V/m)
B	=	incident magnetic flux density (T)
t	=	time (s)

The strengths of the electric and magnetic fields decrease with increasing distance r between the aperture and the conductor.

Responses to the HEMP threat can be of the order of tens of amperes or hundreds of volts on a cable near a hole a few centimeters in radius, and they can be even larger for a long slot aperture. An aperture POE tends to behave as an antenna mounted in the shield surface. A narrow slot performs much like a slot antenna, and can reradiate the HEMP transient to the protected volume inside the barrier. This is the reason that the slots around doors are of particular concern. As the slot becomes wider, the radiation also increases, but not as dramatically as with increasing slot length. The coupling of fields through a given aperture POE will tend to increase linearly with frequency up to a point near aperture POE resonance, when the aperture POE length equals the half wavelength. At lengths much less than these resonant lengths, coupling is still significant and must be addressed.

Three very important characteristics of aperture POEs are highlighted by the coupling relationships in equation 8:

a. Magnitude of the transients that can be induced on interior conductors by aperture leakage increases as the square of aperture dimensions.

b. Since the interactions involve derivatives (rates of change) of the electromagnetic fields, high frequency components are emphasized; thus, apertures that may be acceptable in electromagnetic interference/compatibility disciplines can critically compromise a HEMP barrier.

c. Leakage fields in the protected volume are attenuated with increased distance from the aperture; it is good practice, therefore, to place internal wiring as far away as practical from intentional aperture POEs.

Because of the stringent MIL-STD-188-125 shielding effectiveness requirements, even small unprotected (or poorly protected) apertures will lead to failure during the barrier acceptance test. Therefore, careful attention to detail in design and assembly of the HEMP protection subsystem is essential.

9.1.3 Waveguides-below-cutoff. The laws of electromagnetic, supported by experiment, state that electromagnetic waves will propagate inside a hollow metal tube only at frequencies above a cutoff value such that their wavelengths "fit into" the interior dimensions. These metal tubes or waveguides are commonly used to transmit microwave signals. If the primary purpose is to attenuate electromagnetic waves at frequencies below the cutoff value, rather than propagating signals above cutoff, the waveguide is known as a waveguide-below-cutoff. This principle can be exploited to produce piping and ventilation penetration protection that will allow liquids and air to pass through the barrier, while adequately blocking HEMP fields (section 10). The same approach can also be used to provide partial protection for a personnel entryway.

Only an air-filled rectangular waveguide shown by figure 33 will be discussed in this section, but other shapes and fill materials will be of interest in later sections. The lowest cutoff frequency f_c for this configuration is associated with a transverse electric or transverse magnetic propagation mode, and its value is determined by the dimension of the longer side. Assuming $a \geq b$, then

$$f_c = \frac{c}{2a} = \frac{3 \times 10^8}{2a} \text{ Hz} \tag{9}$$

where c is the speed of light and a is in meters.

Electromagnetic waves at frequencies less than f_c will be attenuated as they propagate through the waveguide, with a loss A in decibels given as a function of the length L in meters by

$$A = 27.3 \frac{L}{a} \sqrt{1 - \left(\frac{f}{f_c}\right)^2} \text{ dB} \tag{10}$$

where f is the frequency. Waves well above the cutoff frequency will pass unattenuated through the guide.

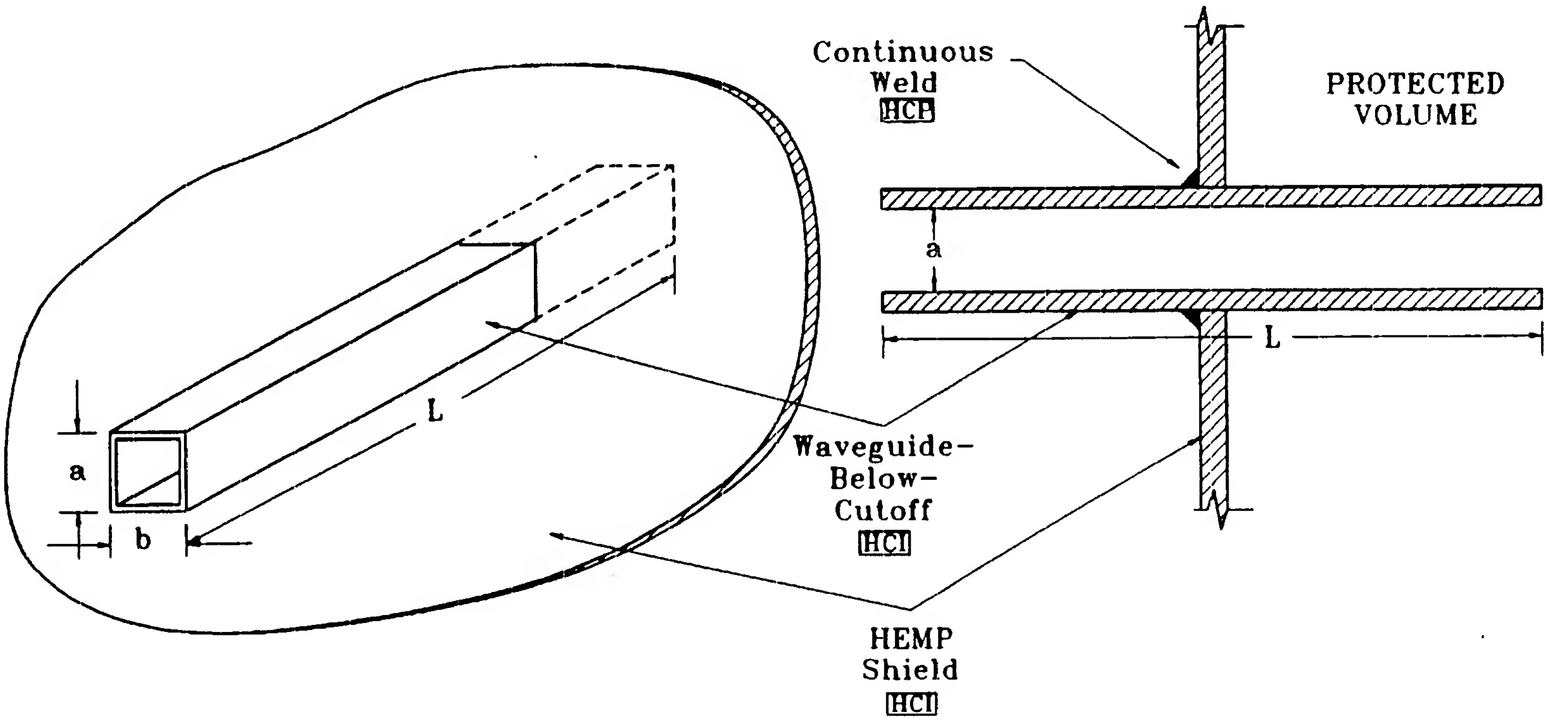


FIGURE 33. **Rectangular waveguide-below-cutoff.**

A waveguide entryway for personnel is typically 2.44 m (8 ft) in height so that individuals can walk comfortably in an upright position. MIL-STD-188-125 requires the waveguide length to be at least five times the diagonal dimension of the cross section; length-to-height ratio (L/a) must therefore be in excess of 5:1. The lowest cutoff frequency f_c for this entryway is found to be 61 MHz from the equations written above, and attenuation in excess of 100 dB occurs only for waves at frequencies below 41 MHz. Thus, the shielding effectiveness requirements of the standard cannot be met at a personnel entryway with a waveguide-below-cutoff alone; shielded doors (electromagnetic closure) must also be provided.

If any conductor is permitted to run longitudinally through the waveguide and is insulated from its walls, a coaxial geometry will be formed. The coaxial configuration supports propagation of transverse electromagnetic waves and negates the cutoff properties of the waveguide. Special installation instructions therefore apply to electrical wiring, conduits, piping, handrails, or other conductors in a waveguide-below-cutoff entryway.

9.1.4 Electromagnetic closure of openings in the shield. This concept is simple and straightforward. A metal plate is placed over the opening as illustrated in figure 34, and leakage around the edges is prevented by providing and maintaining a circumferential rf seal.

Requirements for the cover plate are essentially identical to those for the sheets used to form the basic shield. The plate must be metal to reflect the incident HEMP fields, and its thickness will virtually always be determined by mechanical considerations rather than shielding requirements.

To satisfy 100 dB (nominal) shielding effectiveness specifications, the rf seal must be achieved by metal-to-metal contact between clean, undamaged, and unoxidized materials under approximately uniform pressure applied around the entire circumference of the opening. If any one of these four conditions is not present, degraded electromagnetic performance will result.

Designs for nearly all rf seals can be grouped into three broad classifications, as follows:

a. rf gasketed seals – The electromagnetic seal is formed with three elements. The metal surface of the cover plate is in physical contact with an rf gasket, which is also in contact with the shield surface. An rf gasketed seal used to electromagnetically close the cover of a shielded enclosure is pictured in figure 35. These rf gaskets are

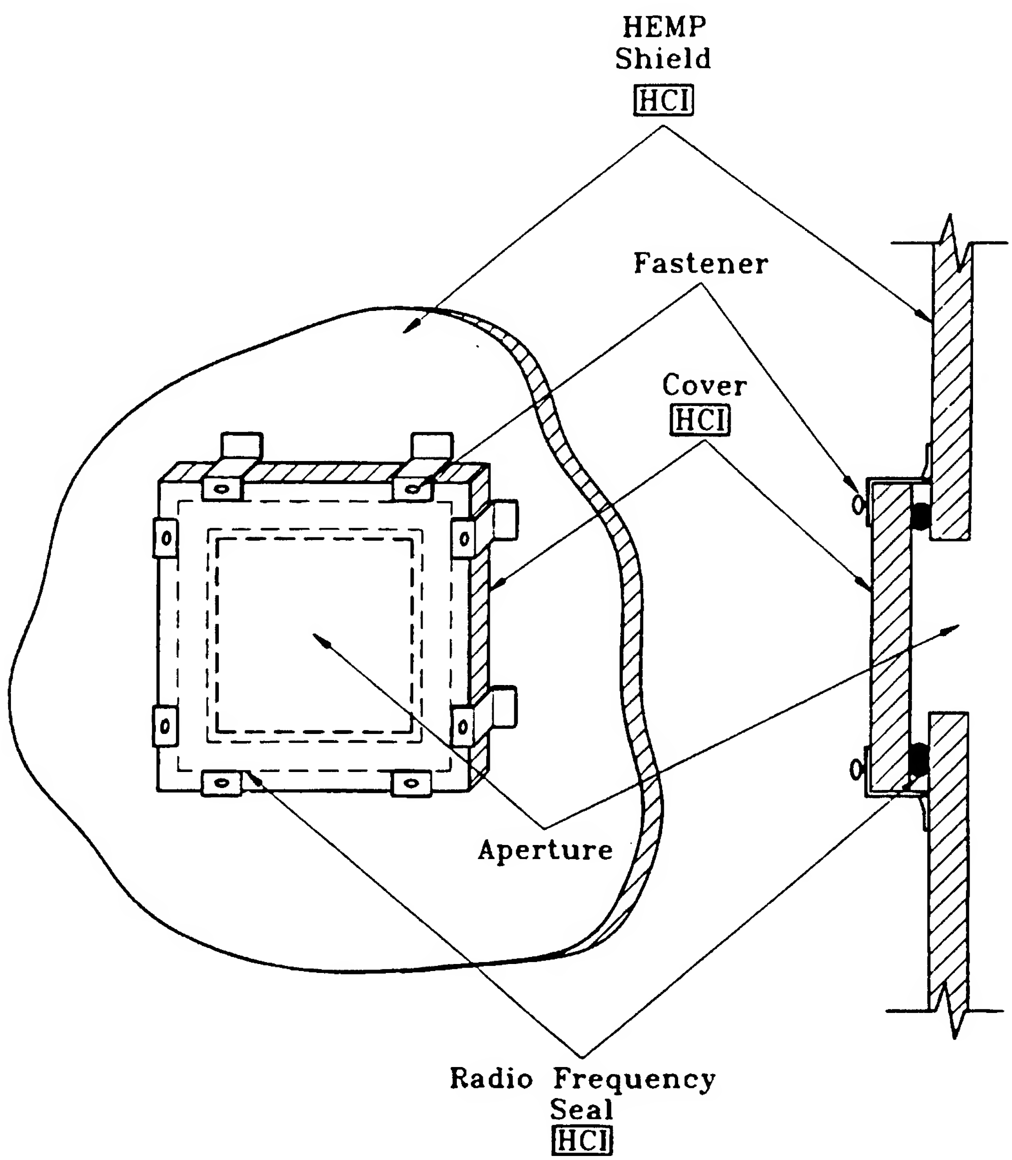
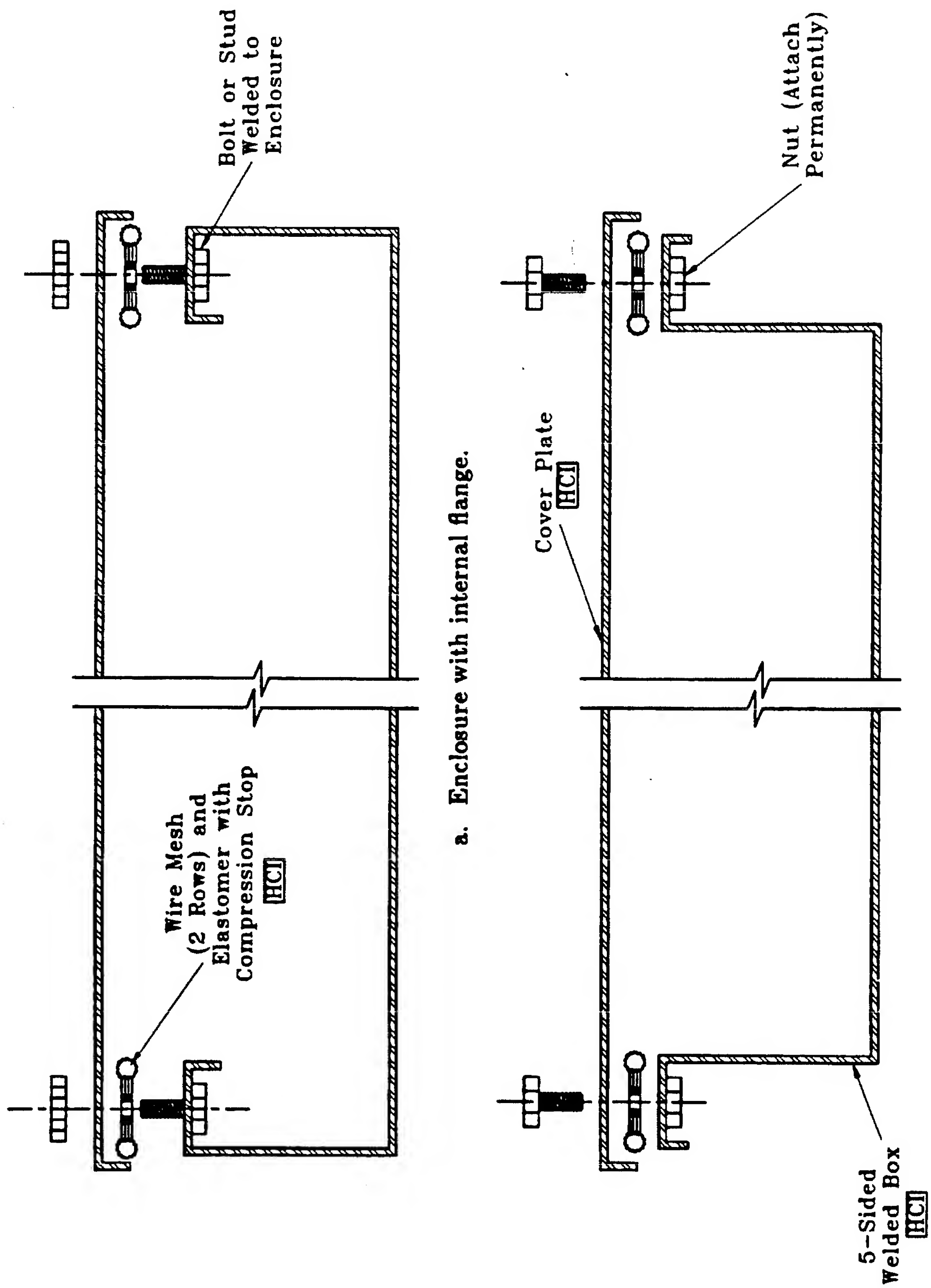


FIGURE 34. Electromagnetic closure.



a. Enclosure with internal flange.

b. Enclosure with external flange (preferred method).

FIGURE 35. Electromagnetic seal with rf gasket.

available in many forms including wire m&h, wire mesh over an elastomer core, and metal impregnated elastomers.

b. Fingerstock seals – This design is similar to an rf gasket seal, except that it uses one or more strips of metal springs or “fingerstock” (figure 36) instead of the gasket. The most common type of fingerstock is made from a beryllium-copper alloy.

c. Flat surface/flat surface seals –This is a two-element seal, with the cover plate surface in direct contact with the shield. To obtain high-quality closure, the mating surfaces are sometimes machined as a matched set.

The pressure needed to compress the rf gasket or fingerstock springs and hold the cover in place is provided by bolting the plate to the shield, or by use of other types of mechanical fasteners. The choice of the fastening method depends on the frequency of cover removal and reinstallation. The requirement to apply nearly uniform pressure around the entire circumference is another key factor in the design.

While electromagnetic closure is conceptually simple, achieving and maintaining a high-quality rf seal is quite difficult in practice. This is due to the inevitable accumulation

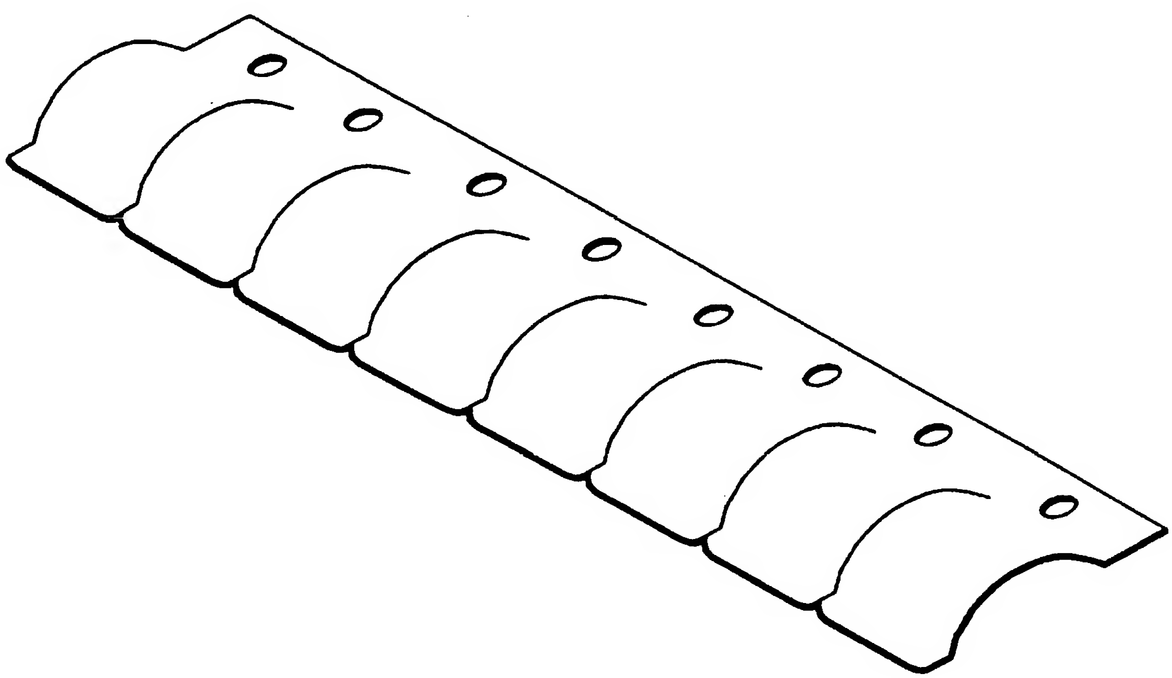


FIGURE 36. Typical fingerstock.

of dirt and grease on closure surfaces and chemical reactions (oxidation and corrosion) of the materials. Cleaning can reverse the degradation by removing the foreign material from the metal-to-metal contact surfaces. However, a means of permanent closure, such as welding the cover in place, should be used whenever practical.

9.2 MIL-STD-188-125 requirements.

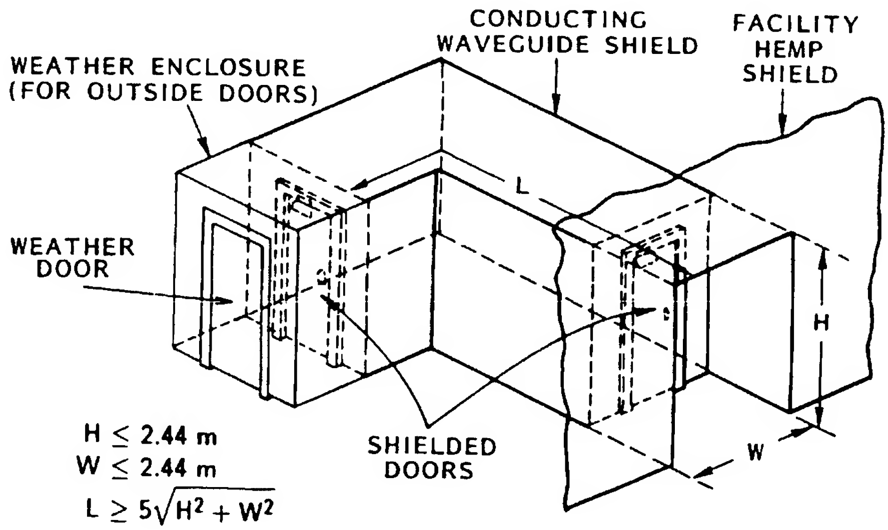
5.1.4.1 HEMP protection for architectural POEs. HEMP protection for architectural POEs, including personnel entryways and exits and equipment accesses through the facility shield, shall be provided with electromagnetic closure, waveguide-below-cutoff techniques, or combinations of closure and waveguides-below-cutoff.

5.1.4.1.1 Quality assurance for architectural POE protective devices. All welded or brazed seams and joints required for installation of architectural POE protective devices shall be monitored under the program of in-progress inspection of welded and brazed seams (see 5.1.3.4.1). Shielded doors and other closure or access covers shall be subjected to electromagnetic and mechanical quality assurance tests to demonstrate acceptable performance.

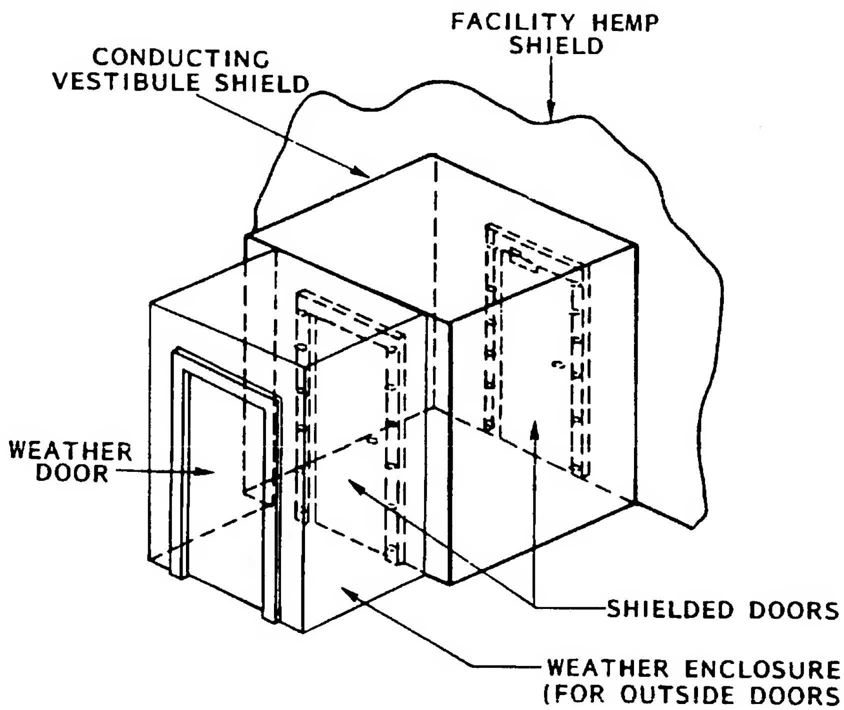
5.1.4.1.2 Acceptance testing for architectural POE protective devices. Acceptance testing for architectural POE protective devices shall be conducted using shielding effectiveness test procedures of appendix A.

5.1.4.2 Personnel entryways and exits. HEMP protection for all normal and emergency personnel entryways and exits shall be provided with a two-door shielded waveguide-below-cutoff entryway or with a two-door shielded vestibule (figure 2). As design objectives, the number of personnel entryways and exits should be constrained to the minimum requirements of NFPA 101 and the main personnel entryway should be a waveguide-below-cutoff.

5.1.4.2.1 Waveguide entryway dimensions. When a waveguide-below-cutoff entryway is used, height and width of the waveguide shall each not exceed 2.44 m (8 ft), and the length of the waveguide along its shortest path shall be at least jive times the diagonal dimension of the cross-section. As a design objective, no electrical wiring, piping, or other conductors should run longitudinally inside the waveguide entryway. Where electrical wiring cannot be eliminated from the entryway, it shall be run in metal conduit. All conduits and other groundable conductors such as pipes or handrails in the waveguide entryway shall be electrically bonded to the entryway shield at intervals not exceeding 1 m (3.3 ft).



a. Waveguide entryway.



b. Vestibule entryway.

FIGURE 2. Typical waveguide and vestibule entryways.

5.1.4.2.2 Entryway shield. The entryway shield shall comply with the same requirements applicable to the facility HEMP shield (see 5.1.3). All entryway POEs , either into the facility protected volume or to the outside, shall comply with the same requirements applicable to other POEs through the electromagnetic barrier (see 5.1.5 through 5.1.7).

5.1.4.2.3 Entryway shield doors. Entryway shield door frames shall be welded or brazed into the entryway shield. When installed, vestibule shield doors shall provide at least the minimum shielding effectiveness shown in figure 1. Waveguide entryway doors shall provide at least the minimum electric and plane wave shielding effectiveness shown in figure 1, but are not required to satisfy the magnetic shielding effectiveness criteria. A weather enclosure with appropriate environmental controls shall be provided to protect exterior shield doors from corrosion and exposure to blown dust and other natural elements.

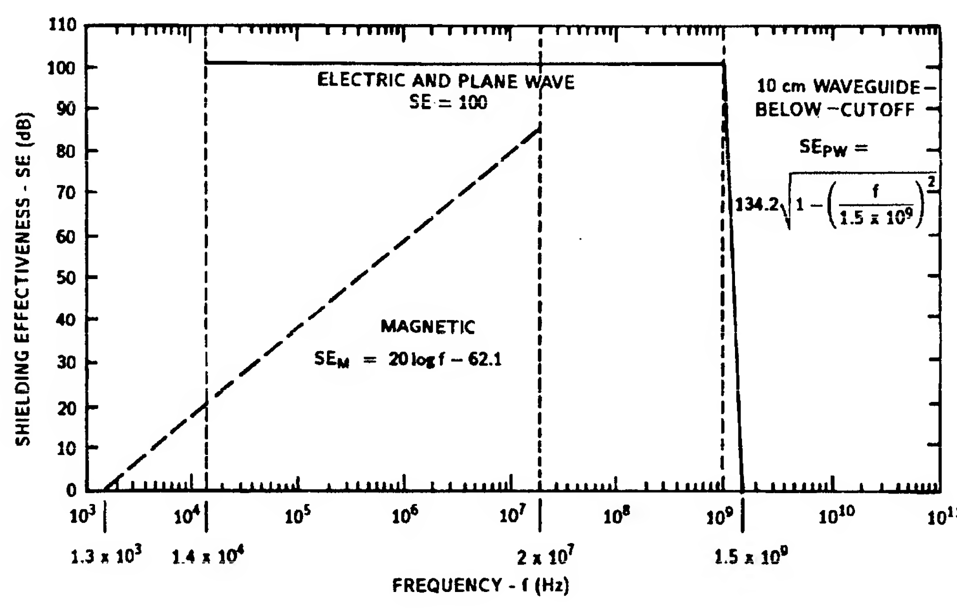


FIGURE 1. Minimum HEMP shielding effectiveness requirement (measured in accordance with procedure of appendix A).

5.1.4.2.4 Entryway interlocks and alarms. The entryway shield doors shall be provided with interlocks to ensure that at least one of the shield doors remains closed except during emergency evacuations. The entryway shield doors shall be provided with an alarm to indicate that the interlock has been overridden or that both shield doors are open.

5.1.4.3 Equipment accesses. A protected equipment access POE shall be provided only when movement of the equipment through a personnel entryway is not practical. HEMP protection for equipment accesses through the facility HEMP shield shall be provided with electromagnetic closure. The metal access cover shall be continuously seam welded in place, if anticipated usage is less than once per 3 years, and shall be radio frequency gasketed and secured by a closure mechanism which ensures a proper gasket seal, when expected usage is more frequent. When closed, the equipment access covers shall provide at least the minimum shielding effectiveness shown in figure 1. A weather enclosure shall be provided to protect exterior gasketed access covers from corrosion and exposure to blown dust and other natural elements.

9.3 Applications. The underlying basis for all of the MIL-STD-188-125 requirements above is the need to provide at least the specified minimum HEMP shielding effectiveness in barrier areas containing these penetrations. The shield performance must be preserved when personnel are routinely entering or leaving the facility. This dictates an entryway design with two shielded doors, with at least one door shut at all times except emergency evacuation situations. The door interlock and alarm circuits prevent inadvertent or unnoticed opening of both doors simultaneously.

Either a waveguide-below-cutoff or a vestibule design is permitted at a personnel entryway, but the waveguide-below-cutoff is preferred for the main entryway. Heavy traffic tends to increase door seal wear and degradation rate, and the waveguide design has better "fail-safe" characteristics. Waveguide dimensional restrictions ensure that the cutoff properties and low frequency attenuation performance are consistent with the reduced shielding effectiveness requirements for waveguide shielded doors. Prescribed treatments of waveguide electrical wiring, conduits, and other longitudinal conductors are intended to prevent formation of a coaxial geometry.

Several MIL-STD-188-125 requirements arise from the difficulty in maintaining performance of rf seals using mechanical fasteners. These include the requirement to weld or braze door frames into the entryway shield, required weather/corrosion protection for exterior shielded doors and access covers, and welded covers on infrequently used equipment accesses. Once again, the term "welding" is sometimes used in a generic sense and includes brazing.

9.3.1 General design guidance. The first principle in designing HEMP protection for architectural POEs is to minimize their number. This improves the quality of the hardening, reduces its construction and testing costs, and relieves the hardness maintenance/ hardness surveillance burden for the future staff. This same principle is also primary for all other types of penetrations.

The number and accessibility of entryways/exits must comply with minimum life safety code requirements of ANSI/NFPA 101 (reference 9-3), but these minimums should not be exceeded except to avoid hazards. One entryway should be designed for all normal traffic where practical, and this entryway should be made as large, comfortable, and convenient to operate as possible. Power-assisted shielded doors should be considered for the main entryway application (see section 18).

All other personnel entryways/exits should be reserved exclusively for emergencies. Use under routine circumstances can be discouraged by the choice of door hardware and the alarm circuit design. Specific measures will be suggested in later subsections.

Designated ports for moving equipment into or out of the facility should not be provided unless use of personnel entryways for this purpose is unreasonable. Therefore, a requirement for an equipment access POE should occur only if the items to be moved are too large to pass through personnel doors.

As a general precaution, interior cabling should not be routed across or near aperture POEs. The spatial variation of penetrating fields with distance from the point-of-entry is a complex function of the aperture shape and size, as well as the electromagnetic excitation. Generally, however, field coupling to a wire in the vicinity of an aperture decreases as the square of the distance. Therefore, internal electromagnetic stresses can be reduced by routing cables as far as practical away from personnel and equipment accesses. The restricted area near the aperture POE is often termed an 'exclusion zone."

Finally, the facility floor plan should be designed so that personnel entryways and equipment accesses are located away from the penetration entry area, if possible. This configuration reduces the facility vulnerability caused by performance degradation or failure of architectural POE protective treatments.

9.3.2 Architectural POE testing. MIL-STD-188-125 prescribes two classes (quality assurance and acceptance) of testing during construction of the HEMP protection subsystem, plus verification testing at about the time of the initial operating capability of the facility. This paragraph briefly discusses the objectives and nature of architectural POE protective device tests. More detailed information on the subject is found in section 16.

The goals of quality assurance testing are to ensure that proper materials and components are used in fabrication and that the assembly is performed correctly. Certifications of the sheet material for the entryway shield construction and in-progress inspection of the welding are included with those for the rest of the facility HEMP shield. Welds for installing architectural POE protective devices must be included in the inspection program.

The specific quality assurance requirement for architectural POEs is shielded door testing. Doors and frames are usually manufactured as a matched set by a single vendor to the buyer's specifications. These specifications should explicitly include electromagnetic and mechanical tests that demonstrate that the product will satisfy the in-service requirements. Testing of the actual door and frame to be delivered is strongly preferred, and recommended testing procedures are included in appendix A.

Acceptance and verification testing of architectural POE protection is performed as an integral part of the overall barrier test. The test plans should be carefully reviewed, however, to ensure that measurement locations have been selected for evaluating the performance of the architectural POE protective devices.

9.3.3 Personnel entryways. The obvious method for allowing personnel to enter and leave a shielded area is to install a shielded door in the electromagnetic barrier. This simple solution, however, has a serious shortcoming. Whenever the door is opened, which occurs many times each day at a manned facility, the shield becomes compromised. Installing a shielded vestibule with two interlocked rf doors extends protection to the period of actual entries and exits, and this is one of two approaches in MIL-STD-188-125 for HEMP hardening at a personnel entryway.

The vestibule entryway is traditional and theoretically sound. In practice, however, its effectiveness may be limited because it is so difficult to maintain high electromagnetic attenuation of high-usage shielded doors. The problem can be partially circumvented with a waveguide entryway design.

The physical structure of a waveguide entryway supplies the electromagnetic isolation at frequencies in the lower part of the HEMP threat spectrum. While interlocked shielded doors are still necessary for high frequency protection, their performance requirements are somewhat relaxed by elimination of the magnetic shielding effectiveness specification because of the low frequency rejection provided by the waveguide. Furthermore, in the event of degraded door performance or if both doors are simultaneously open, only the higher threat frequencies will leak to the interior. Reduced maintenance requirements and this partial "fail-safe" behavior are the principal reasons for preferring a waveguide design for the high-traffic, main personnel entryway.

Reference 9-4 describes the recent development of a labyrinth waveguide entryway, which is lined with rf absorbent material and requires no rf shielded doors. This technology is not yet mature, and MIL-STD-188-125 does not presently permit this method of hardening at a personnel entryway.

Shielded doors must not be exposed to outside weather because dirt and moisture will rapidly degrade their attenuation characteristics. Regardless of the type of entryway selected, therefore, all exterior doors must be protected with a weather vestibule.

9.3.3.1 Waveguide-below-cutoff entryway. A waveguide-below-cutoff entryway is essentially a hollow metal (shielded) tube or tunnel with the waveguide properties described in 9.1.3. Because tunnel dimensions needed to accommodate personnel comfortably must be much larger than the wavelength corresponding to 1.5 GHz, waveguide-below-cutoff attenuation occurs only for frequencies in the lower part of the HEMP spectrum. Therefore, two interlocked shielded doors are still required to provide the high-frequency isolation.

All waveguide entryway shield surfaces are part of the primary electromagnetic barrier. Therefore, the entryway shield must be fabricated with the same care and quality controls and must satisfy the same effectiveness criteria as the rest of the facility HEMP shield. Virtually all requirements, practices, and precautions presented in section 8, 'Shields and Shielding: also apply to entryway shield construction and testing.

For the same reason, penetrations of waveguide entryway shield surfaces must be minimized. Entryway POEs can generally be limited to those required for shielded door operation and tunnel lighting and ventilation. Mechanical, structural, or electrical points-of-entry that cannot be eliminated must be protected in accordance with requirements of the standard and guidance in sections 10, 11, and 12.

Figure 37 shows a plan view of the waveguide-below-cutoff main personnel entryway design for a satellite communications facility. This example is presented because it is technically sound and illustrates several innovations. Noteworthy features include the following:

a. The architect has provided access into two separate areas with a single entryway; this represents a significant cost savings compared to individual entryways for each space.

b. The waveguide shares a common wall with the protected volume. Entryway lighting could be supplied through waveguide-below-cutoff arrays in the sidewall. Furthermore, electrical POEs for door interlock and alarm circuits can be located so that no longitudinal electrical wiring runs are required.

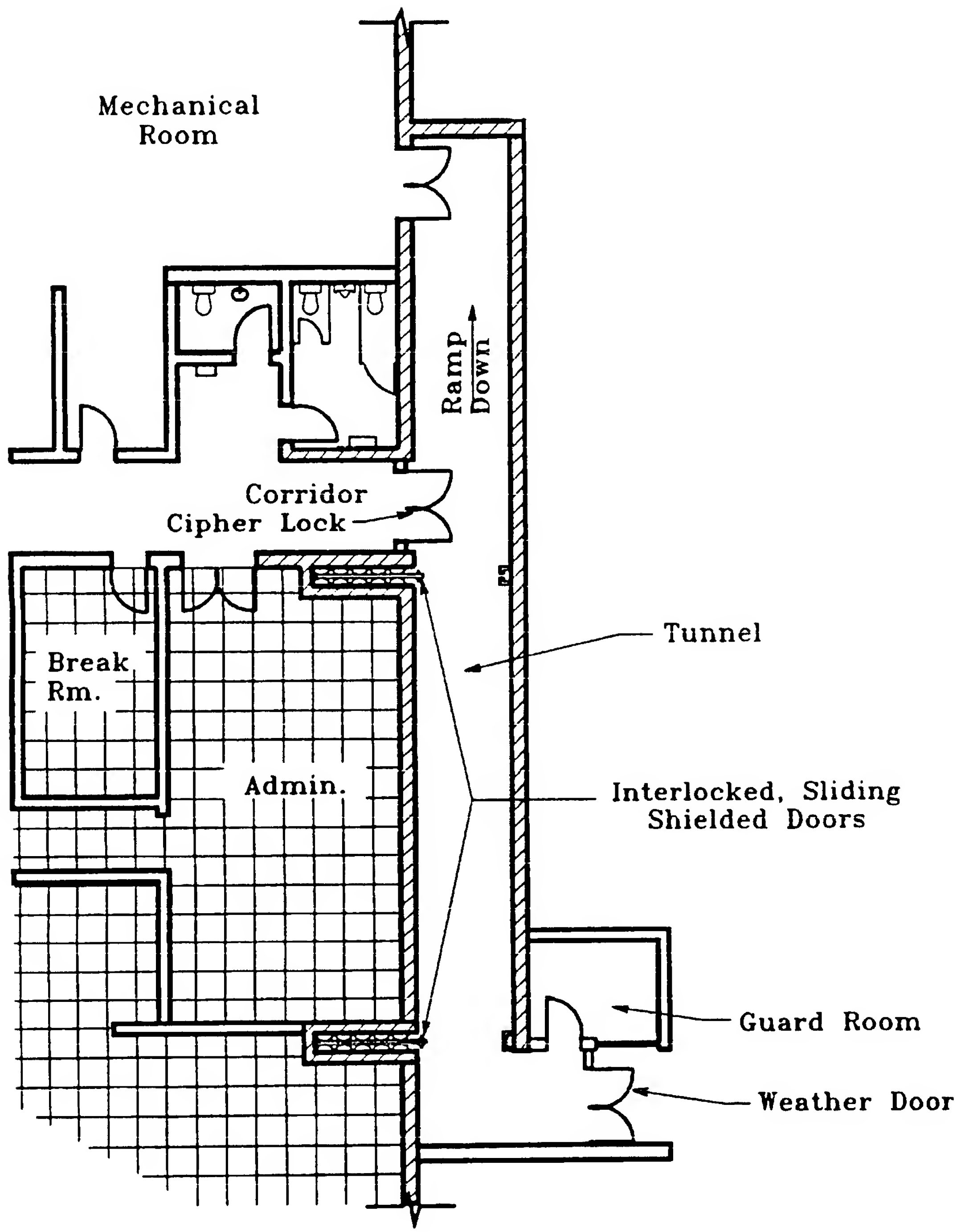


FIGURE 37. Example of main personnel entryway.

c. A weather protecting enclosure is provided at the exterior end of the waveguide.

d. Entry into the operations area requires operation of a cipher lock. A separate door was installed for this purpose, rather than attempting to incorporate the lock into a specially designed shielded door.

e. Both sections of the entryway incorporate a 90-degree bend in the leakage propagation path.

f. Part of the waveguide length into the operations area extends into the protected volume. The tunnel can be outside the main barrier, inside the protected volume, or a combination so long as the required length-to-transverse dimension requirement is satisfied.

Fundamental configuration requirements for a waveguide-below-cutoff entryway relate to its dimensions. Height should be large enough to permit personnel to stand erect within the tunnel, but it must not exceed 2.44 m (8 ft). Tunnel width should be chosen to allow side-by-side passage, but it should usually be less than the height. Length of the waveguide along its shortest path must be at least five times the diagonal dimension ($5 \times \sqrt{a^2 + b^2}$).

A waveguide entryway designated for routine traffic should be as large and comfortable as practical, within the above constraints. However, it should be recognized that every increase in height or width produces corresponding increases in tunnel length, waveguide shield surface area, and entryway cost.

Placement of the waveguide entryway relative to the building floor plan is not specified in the standard. All of the configurations shown by figure 38 and a nearly limitless number of other possible arrangements are allowable. Factors to be considered in choosing the layout for a particular facility include traffic flow patterns, waveguide entryway electrical design requirements, and cost. As mentioned earlier, the waveguide tunnel can be outside the primary barrier envelope (configurations a and d), inside the envelope (configurations b and e), or partly outside and partly inside (configurations c and f). Configuration a requires the largest lot size. Configurations b and c restrict personnel movements between some areas of the building. Configurations with a common entryway/barrier shield wall, as in b, d, and e, are advantageous in designing the waveguide electrical installation (see 9.3.3.1.2).

At least one 90-degree bend (configurations d, e, and f) is also desirable, although not required by the standard. The bend provides more graceful degradation of entryway isolation, if electromagnetic leaks develop in the shielded door seals.

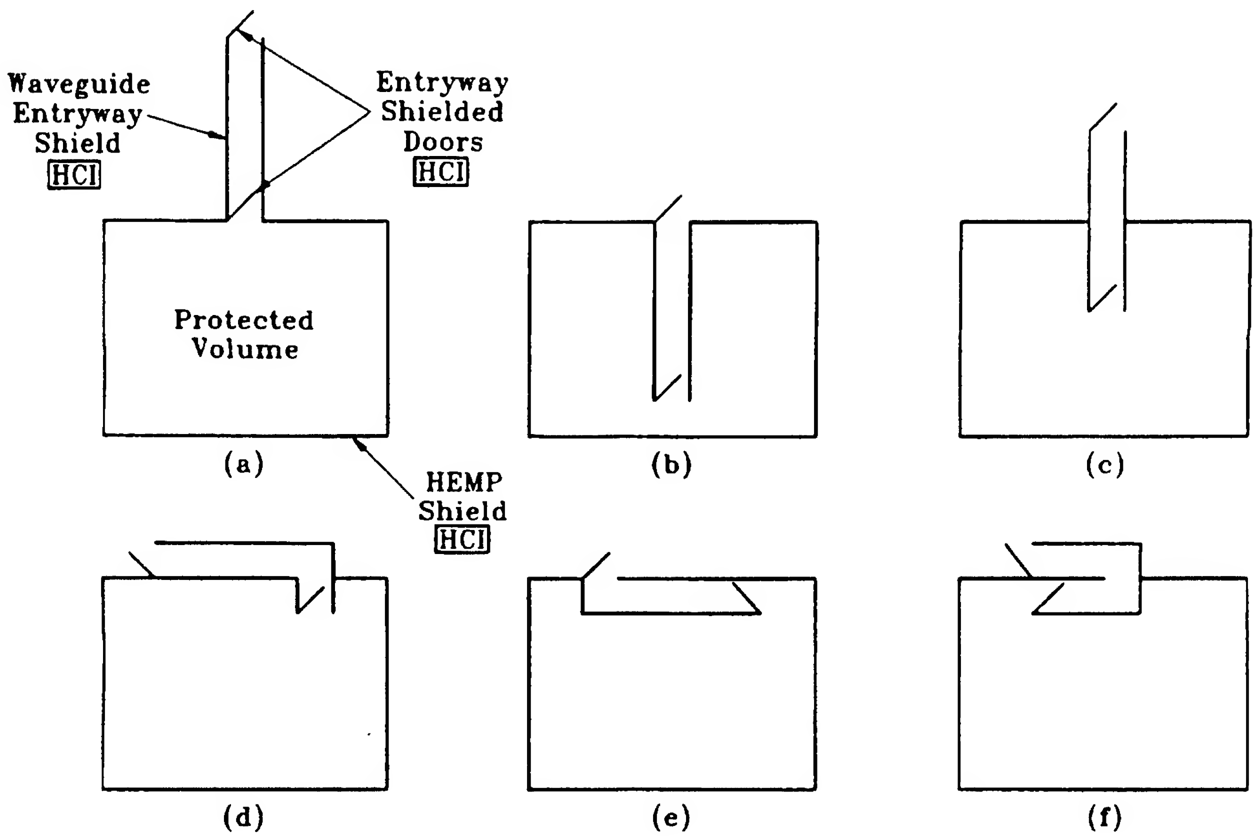


FIGURE 38. Waveguide entryway configurations.

Figure 38 is also meant to recommend that shielded doors be placed at the ends of the tunnel, although such placement is not a technical necessity. The important point in this area of the design is to provide sufficient space between doors for the number of people expected to be simultaneously entering or leaving the protected volume.

Finally, it is recommended that a waveguide-below-cutoff entryway have little or no interior finish work. There are two fundamental reasons for this suggestion. First, the waveguide dimensions will be increased by the thickness of the interior finish, or the waveguide opening will be decreased by this amount. Secondly, trim strips may inadvertently create ungrounded longitudinal conductors which destroy the cutoff properties.

9.3.3.1.1 Waveguide entryway shield. The waveguide entryway shield consists of wall, floor, and ceiling surfaces of the tunnel and the two transverse walls which contain the in-line shielded doors. As required by MIL-STD-188-125 and as discussed in section 8 of this handbook, the waveguide entryway shield must be constructed from steel or copper plate. All seams and joints between adjacent panels must be continuously welded for a steel shield or continuously brazed for a copper shield. This includes the circumferential joints between the transverse walls and the tunnel shield, as well as the circumferential wall-to-door frame seams.

There are very few aspects of shield design, construction, and testing which are unique to a waveguide entryway. Factors in selecting the steel or copper alloy, sheet thickness, seam design, and corrosion control approach are virtually identical to considerations for design and construction of the rest of the facility HEMP shield. Furthermore, performance requirements for both sections are the same.

The only element of entryway shield testing that is unique to a waveguide occurs when a shielded door is not at the end of the tunnel. In this instance, it is not possible to perform acceptance testing on the part of the entryway shield which is beyond the outer door or inside the inner door. The in-progress inspection of seams must, therefore, be done with extreme care. This complication is avoided when the shielded doors are placed at the ends. It is recommended, furthermore, that the cutoff properties of the waveguide tunnel be demonstrated by a test with both doors open, as part of the shielding effectiveness testing.

9.3.3.1.2 Waveguide entryway electrical installations. MIL-STD-188-125 establishes a design objective of completely eliminating longitudinal runs of electrical wiring, pipes, or other conductors in a waveguide entryway tunnel. The purpose of the objective is to avoid geometries which could compromise the waveguide cutoff characteristics.

Elimination of longitudinal wiring runs is quite easily realized when the tunnel and the protected volume have a common shield wall (i.e., configurations b, d, and e in figure 38). It is accomplished by locating the electrical point-of-entry and POE protective device on the shared shield wall immediately adjacent to the point of use, as shown by figure 39. Within the tunnel, the wiring and conduit then run entirely in a transverse plane.

When door operations and interlocks/alarms are pneumatic or hydraulic, the same approach can be applied. The POE protective devices will be waveguide-below-cutoff pipe stubs, and piping runs are made in the transverse plane.

It is also possible to light the entryway without creating electrical POEs. Figure 40 illustrates one such design approach. Acrylic (nonconductive) tubes are used to transmit the light through the common shield, which separates the entryway volume from the protected volume. These 'light pipes" penetrate the shield through waveguide-below-cutoff protective devices, similar to those provided for piping and fiber-optic POEs (see section 10). The lamps, which require an ac power input, remain entirely within the protected volume.

A second entryway lighting concept that requires no electrical POEs is shown in figure 41. Lighting fixtures, which are located in the protected volume, illuminate the entryway through waveguide-below-cutoff arrays in the ceiling shield (assuming that the space above the tunnel is inside the barrier) or in the common shield wall. The waveguide arrays are constructed and installed in the same manner as a ventilation POE protective device (see section 10). Welded WBC panels with a relatively large cell size are recommended; numerous problems have been experienced in the field when commercial honeycomb WBC arrays have been used in this application. Ordinary lighting fixtures are used, and they must be installed in a configuration that permits easy replacement of bulbs. To obtain more uniform lighting intensity, diffuser plates may be placed within the entryway.

In other arrangements of the waveguide entryway, such as configuration a of figure 38, longitudinal wiring runs cannot be eliminated unless the conductors are allowed to exit from the shielded volume. Even if wiring is protected inside rigid steel conduit, this is undesirable. In such cases, the electrical lines are run through the tunnel in metal conduit, which is installed as follows:

a. The conduit is run as close to the entryway shield wall as practical.

b. The conduit is electrically bonded to the waveguide shield at intervals not exceeding 1 m.

c. Penetrations of the transverse walls are properly protected.

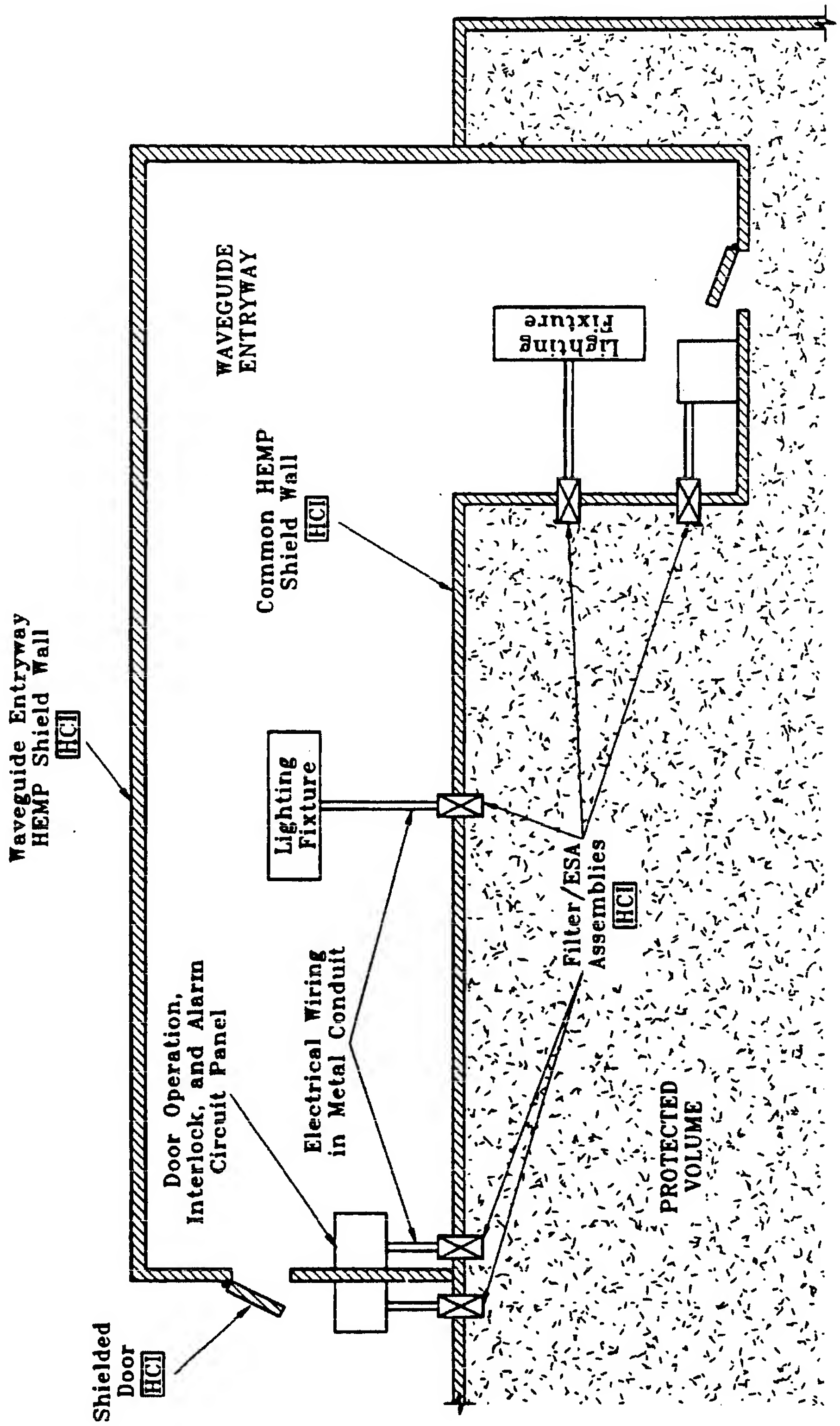


FIGURE 39. Waveguide entryway electrical installation without longitudinal conduits.

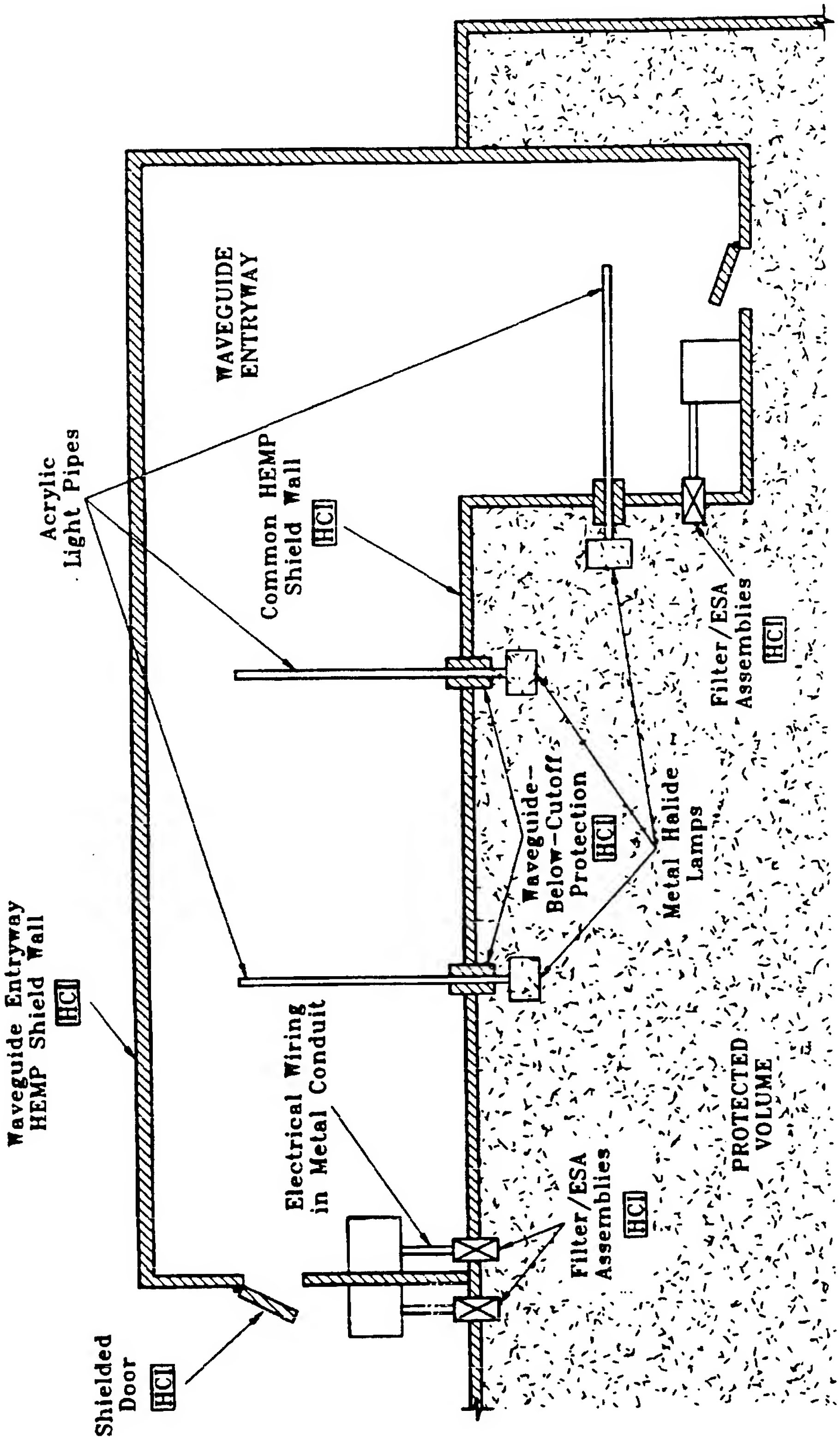


FIGURE 40. A lighting concept providing light transmission through acrylic tubes.

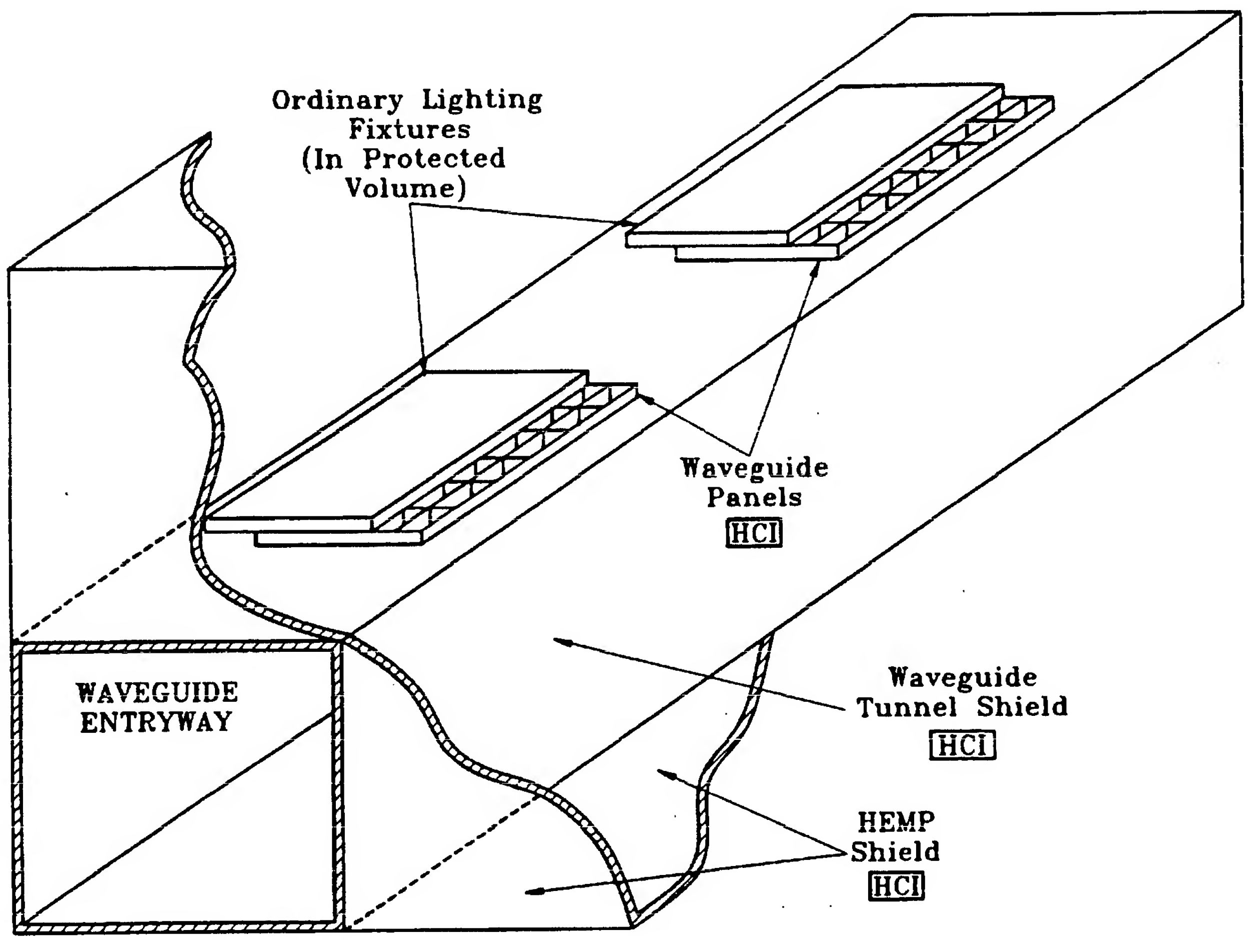


FIGURE 41. Entryway lighting through waveguides-below-cutoff.

Rigid steel conduit is preferred, and couplings should be threaded and welded.

Other groundable conductors such as pipes or handrails, if they cannot be eliminated from the entryway, must be treated in the same manner as conduits.

9.3.3.2 Vestibule entryway. The alternative to a waveguide-below-cutoff entryway is the vestibule entryway with interlocked shielded doors, as pictured in MIL-STD-188-125. If the outer door is open and the inner door is shut, the vestibule area is topologically outside the electromagnetic barrier and experiences essentially full HEMP threat fields. The vestibule is within the protected volume when the outer door is shut and the inner door is open, and the benign electromagnetic environment must be maintained. All surfaces of the vestibule shield must therefore meet barrier requirements, and all design, construction, and testing guidelines of section 8 fully apply.

HEMP protection considerations impose no shape or dimensional requirements on the vestibule entryway. Therefore, the size is determined exclusively by personnel traffic and cost analysis. It is desirable to place the shielded doors in vestibule walls that are perpendicular to each other, but MIL-STD-188-125 does not dictate such a configuration.

There are no entryway-unique requirements regarding vestibule shield penetrations, and there are no special rules for treating electrical wiring and other conductors in the vestibule area. The general principle of POE minimization and the standardized requirements for POE protection, however, are both applicable to vestibule shield penetrations.

9.3.3.3 Shielded doors. Whether a vestibule or a waveguide-below-cutoff entryway design has been selected, MIL-STD-188-125 requires two interlocked shielded doors to be installed as part of the POE hardening. Vestibule doors must satisfy the same effectiveness requirements as the HEMP shield. Note that vestibule shielded doors do not have the attenuation advantages of a waveguide entry tunnel. Waveguide entryway shielded doors must provide 100 dB electric field and plane wave attenuation from 14 kHz to 1 GHz (as installed), but are not required to meet the magnetic shielding effectiveness limits because the waveguide itself provides the low-frequency attenuation.

Commercially-available shielded door designs can generally be categorized into three groups, corresponding to the three types of rf seals described in paragraph 9.1.4. They are rf gasketed shielded doors, fingerstock shielded doors, and doors employing flat surface-to-flat surface rf seals. The third category includes swinging and sliding bellows-operated designs and magnetic doors.

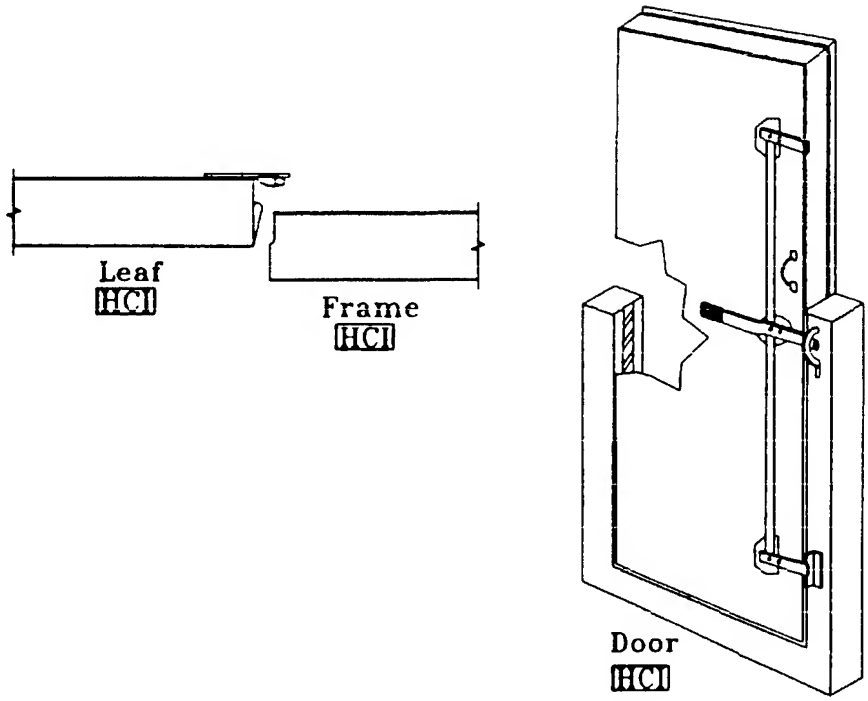
Shielded doors of all three types have been procured to 100 dB (nominal) attenuation performance specifications and have been accepted, on the basis of valid and satisfactory testing. In-service performance at this level of shielding effectiveness, however, has too often been less than reliable for products in all classes. Electromagnetic isolation characteristics can degrade relatively quickly, and various mechanical failures have been experienced. Careful evaluation of maintainability and mechanical soundness of the door design during the selection process and an active maintenance program after installation are the only methods with proven effectiveness for circumventing these problems.

9.3.3.3.1 Shielded doors with rf gasketed seals. The principal advantages of rf gasketed shielded doors are that they can be designed with mechanical simplicity and very light weight. However, maintaining 100 dB (nominal) performance in high-use applications is more difficult with gasketed seals than with other door types. Employment of rf gasketed shielded doors is normally restricted to transportable shelters for these reasons, and they will not be discussed further here.

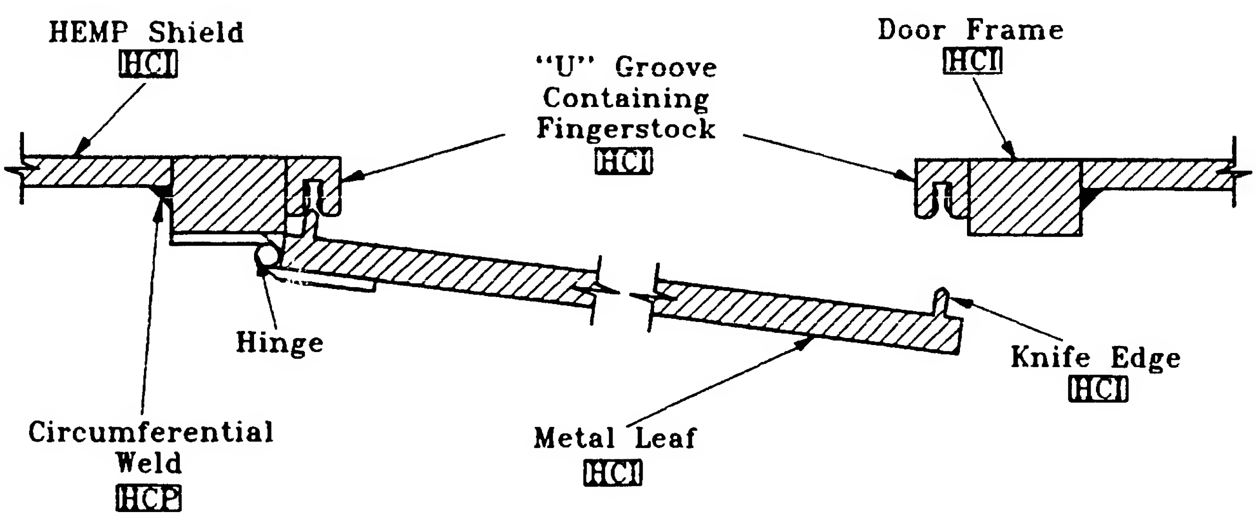
9.3.3.3.2 Fingerstock shielded doors. Figure 42 illustrates two seal designs for fingerstock shielded doors. There are many other variations on the market, including sliding fingerstock doors. The design of figure 42a was principally developed for installation in a shield constructed with two electrically isolated metal skins, but it is also compatible with a single layer shield. As the door closes, friction creates a wiping action to remove dirt and oxides from the electromagnetic mating surfaces. Compression of the fingerstock spring material then produces the required metal-to-metal contact. The main disadvantage is that the fragile fingerstock material is relatively exposed and rather easily damaged.

The knife edge/fingerstock design shown by figure 42b recesses the fragile material into a protected U-groove, thereby preventing mechanical damage from casual contact. This arrangement, however, is relatively sensitive to slight door misalignments.

9.3.3.3.3 Bellows-operated shielded doors. The bellows-operated door (figure 43) is first moved to the closed position, and the sealing sequence is then initiated. Sealing may include an initial step to ensure proper alignment of the leaf with respect to the frame. The bellows is then inflated pneumatically or hydraulically, compressing the metal skin of the door against the matching shield surface on the frame. This approach has excellent potential for distributing the seal pressure around the entire circumference of the door. Its principal disadvantages are that electromagnetic surfaces are relatively exposed and subject to damage, operation provides little self-cleaning action, bellows failures have been experienced, some models have poor repair access, and operating times are usually 10 to 25 seconds. Due to the long operating times, bellows-operated doors are not recommended for high-traffic personnel entryways.

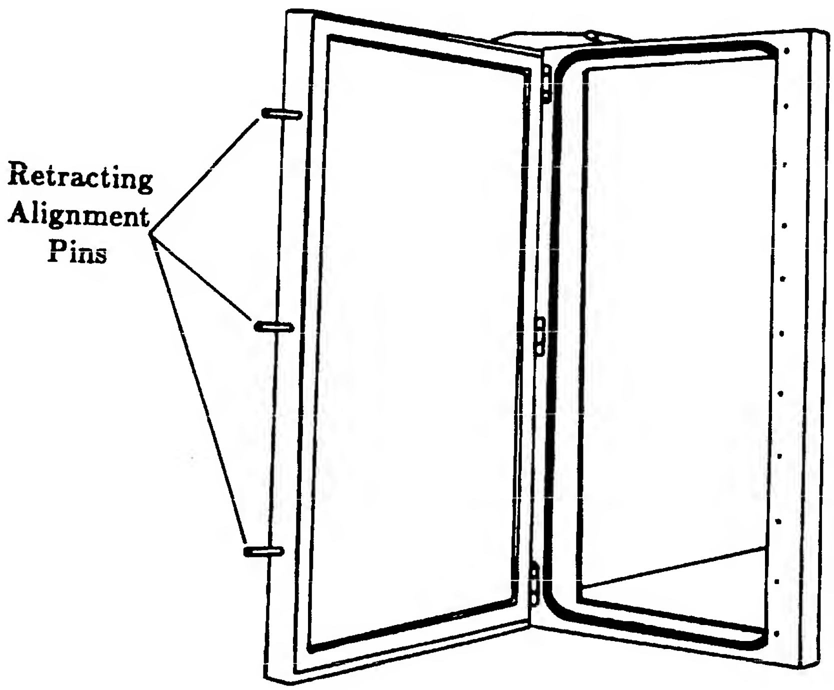


a. Exposed fingerstock design.

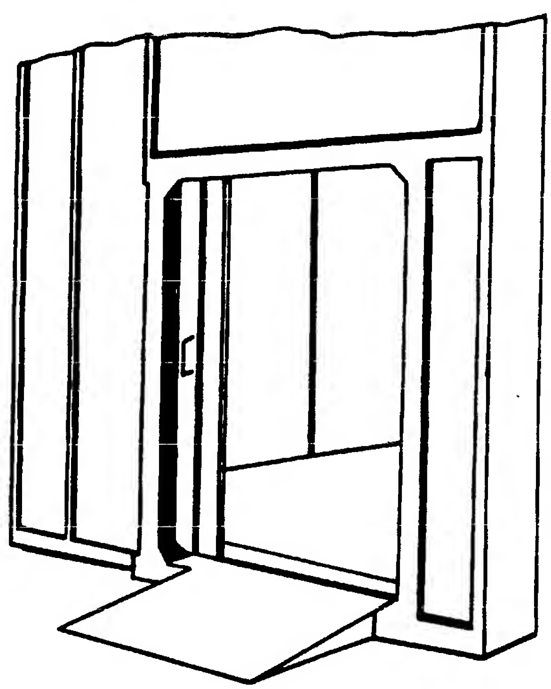


b. Knife edge/fingerstock design.

FIGURE 42. Two seal designs for fingerstock shielded doors.



a. Swinging bellows door.



b. Sliding bellows door.

FIGURE 43. Two designs of bellows-sealed doors.

9.3.3.3.4 Magnetic shielded doors. One magnetic door design uses embedded permanent magnets to force contact between shielding membranes on the door and frame. The seal design is simple and has no fragile components. However, the electromagnetic surfaces are exposed and no wiping action serves to remove dirt and oxidation.

Shielded door designs employing electromagnets or a combination of permanent magnets and electromagnets have recently been introduced and are pictured in figure 44. The leaf consists of a steel sheet and a supporting structure; permanent magnets, if used, will also be installed in the leaf. Steel rails that act as the pole faces of the electromagnet and the coil are mounted on the frame. When the electromagnet is energized in the CLOSE polarity, it attracts the leaf and pulls the door shut.

Advantages of the magnetically operated door are mechanical simplicity and light weight of the leaf. The leaf therefore moves easily and should be mechanically reliable. The principal disadvantage is the criticality of the smooth, flat surfaces on the exposed rails and the mating surface on the leaf. At the time of publication of this handbook, DoD has little in-service experience with this new design.

9.3.3.3.5 Shielded door selection. There is no unanimity among HEMP designers, builders, and users regarding the best and most reliable door design. At the present time, however, the knife edge/fingerstock shielded door is the most frequently chosen type.

Operating characteristics and mechanical designs of the hinge and latching mechanisms are important factors in selecting the shielded door. Power-assisted operation is suggested for the main personnel entryway, ensuring that the door fails in an unlatched (or open) condition on loss of the power source. Manual doors must operate with forces within limits prescribed under safety/human engineering standards in ANSI/NFPA 101 and MIL-STD-1472 (reference 9-5).

Heavy-duty hinges, frames, and mounting hardware are required to prevent sagging of heavy shielded doors and to maintain the precise alignment required for effective rf seals. Multipoint latching should be employed to distribute pressure on the seals around the entire door circumference. Door handles, bolts, or other conducting mechanisms which penetrate the door must be provided with rf seals to prevent electromagnetic leakage along the shaft.

The following recommendations to the designer are made with the intent of preventing damage during construction and minimizing future problems for the operator in maintaining shielded door electromagnetic performance:

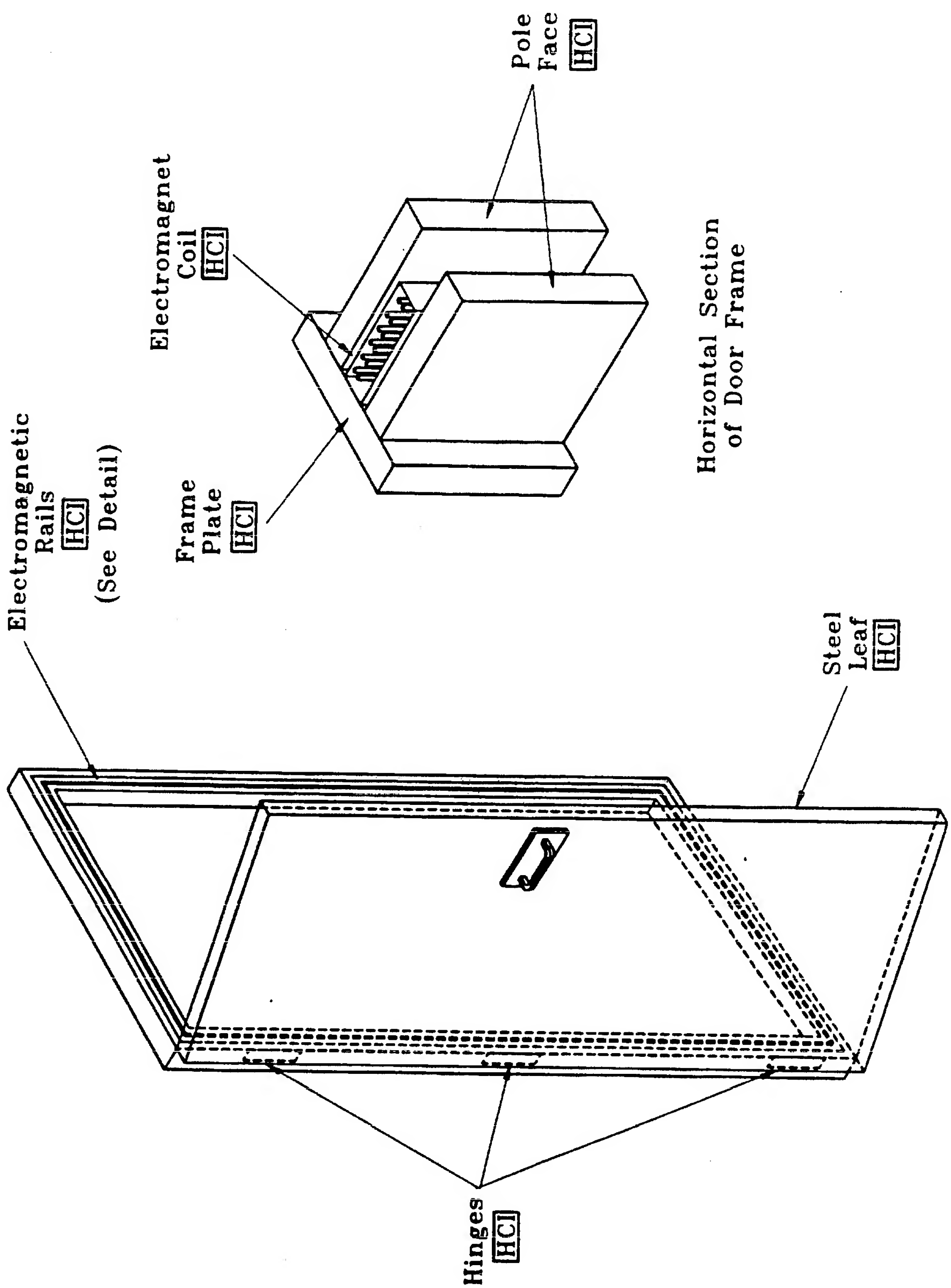


FIGURE 44. Magnetically operated shielded door.

a. Carefully evaluate the seal design for maintainability. It may be necessary to completely disassemble the closure, including removal and reinstallation of fingerstock, to thoroughly clean the seal.

b. Specify mechanical characteristics and mechanical quality control sufficient to ensure that the door operates without major failures for the required number of cycles.

c. Protect shielded doors from extreme temperatures, moisture, blowing dirt or salt spray, and other corrosive conditions. (An environmentally controlled weather vestibule is required by MIL-STD-188-125 for protecting outside shielded doors from such environments.)

d. Provide ventilation waveguide-protected POEs in the door or in the shield wall near the door; this will equalize pressure across the door, minimize air flow through rf seals, and make the door easier to open and close.

e. Discourage routine use of entryways designated for emergencies by removing door hardware at the outer side, posting warning signs, or other measures. Emergency exits should be equipped with alarms.

f. Require cycle counters or timers which indicate when routine maintenance is scheduled, or implement other schemes which encourage or facilitate maintenance.

g. Incorporate human engineering in accordance with MIL-STD-1472 (see section 18).

h. A door and frame are normally purchased as a matched set from a single source. Many vendors can provide electric, pneumatic, or hydraulic power-assisted operating mechanisms for their products, and most will also install the assembly into the HEMP shield if contracted to do so. It is recommended that the door manufacturer perform or supervise the installation.

i. Supply temporary wooden protectors or pads to shield rf seals from damage when moving equipment through doors, and install permanent threshold ramps near the entryway.

j. Ensure that maintenance supplies, repair parts, and test and repair procedures are supplied with the door.

9.3.3.4 Door interlock and alarm circuits. Door interlocks and alarms are intended to assist personnel entering or leaving the protected volume in using the entryways correctly. The system described here also includes a remote indicator panel in the main operating area, with the secondary purpose of informing the facility supervisor regarding entryway status.

The two doors in series in an entryway are to be interlocked so that, under normal conditions, at least one of them is shut at all times. The ability to override the interlock in emergencies, in the event of circuit malfunction, or if one of the doors is inadvertently left open is essential. These requirements can be satisfied with an interlock circuit that performs the following functions:

a. Senses the position, open or shut, of each door.

b. Provides an open-permissive or open-nonpermissive logic signal to the operating circuit of each door, depending on the position of the opposing door.

c. Provides a local override-on-demand switch.

d. Automatically overrides the interlock when a fire or other emergency alarm occurs and upon loss of interlock circuit power.

The interlock system may be pneumatically, hydraulically, electrically, or fiber optically implemented.

Positive interlocks are preferred. If the door operation is entirely manual, however, the interlock circuit must activate status lights or other indicators. Operating or indicator panels must be provided on both sides of each door.

The alarm circuit supplements the interlocks by signaling the operator when an incorrect sequence is initiated. Two alarm levels are recommended. A "danger" (red condition) alarm should be sounded if the HEMP hardening is compromised; this condition exists when both doors in an entryway are open at the same time. A "caution" (yellow condition) alarm signals that an interlock override is activated. A warning signal might also be used to indicate if either door of an entryway designated as an emergency exit only is opened.

Local audible and visual alarms should be provided at the entryway, with a capability to silence the audible signal. A remote alarm panel in the main operations area of the facility is also suggested. It is recommended that the interlock and alarm circuit receive power from an uninterruptible power source.

9.3.3.5 Entryway shield points-of-entry. An entryway is expected to have few points-of-entry other than the personnel doors, and the designer should make every reasonable effort to minimize the number of penetrations. Typically, only the following additional POEs should be permitted:

a. Pneumatic, hydraulic, electrical, or fiber optic POEs associated with power-assisted door operation and door interlocks and alarms

b. Waveguide-below-cutoff arrays to admit light or electrical power POEs for entryway lighting

c. Ventilation POEs in the door or entryway shield, to equalize pressure on both sides of the door and prevent air flow through the seals

All POEs which remain after the minimization process must be protected. Requirements for HEMP hardening at mechanical penetrations are discussed in section 10, and electric POE protection is addressed in section 12.

9.3.4 Equipment accesses. When access is solely for the purpose of infrequent changeout of major hardware items such as diesel generators, it is not necessary to design for rapid cover removal and reinstallation. This allows a more reliable rf seal to be provided.

MIL-STD-188-125 requires the access cover plate to be welded in place if projected usage is less than once per three years. As needed, the patch is cut out of the shield and removed. After the equipment exchange has been completed, the cover is replaced, rewelded, and retested for shielding effectiveness. Requirements on the cover plate will be generally the same as those for any other section of the facility HEMP shield (section 8), except for two differences suggested by the function. The plate must be constructed with sufficient strength and rigidity to allow it to be lifted and moved without distortion or other damage. The plate should also be larger than the required opening, and it should be attached to the underlying shield with lap welds. The cutting operation is therefore not required to preserve critical dimensions.

Figure 45 illustrates a possible design for a 2.5 x 2.5 m (8 x 8 ft) welded equipment access cover. The exterior construction and interior finish in the area of the access port should also be designed for removal, in order to expose the shield.

When the anticipated usage is more frequent than once every three years, an rf gasketed seal is permitted. There are numerous gasket and fingerstock designs intended for use in 100 dB (nominal) shields. Satisfactory results have been obtained with a gasket design consisting of a double row of monel or tin/copper/steel mesh combined with an elastomer separator (see figure 46). It is also recommended that the electromagnetic mating surfaces be nickel- or tin-plated for corrosion resistance. To prevent excessive gasket compression, compression stops should either be imbedded in the elastomer or attached to one of the mating surfaces.

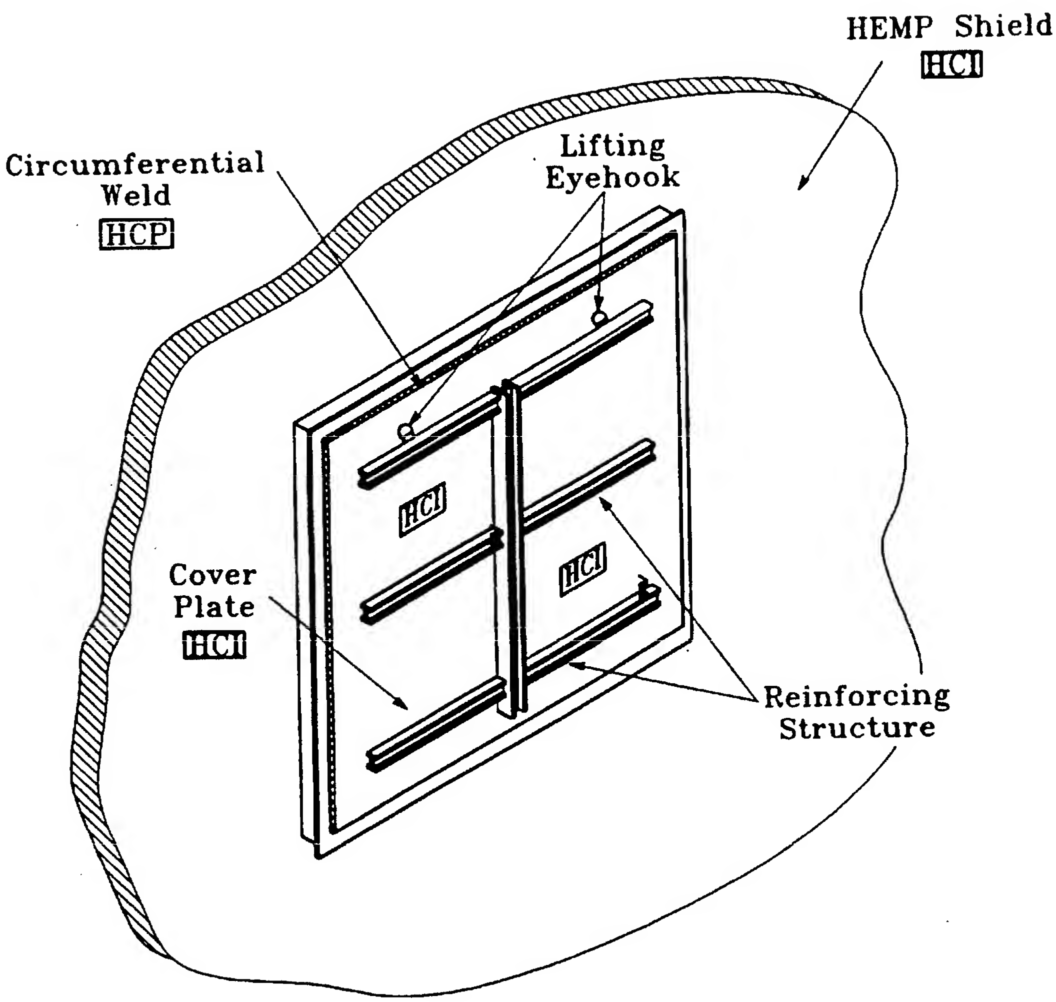
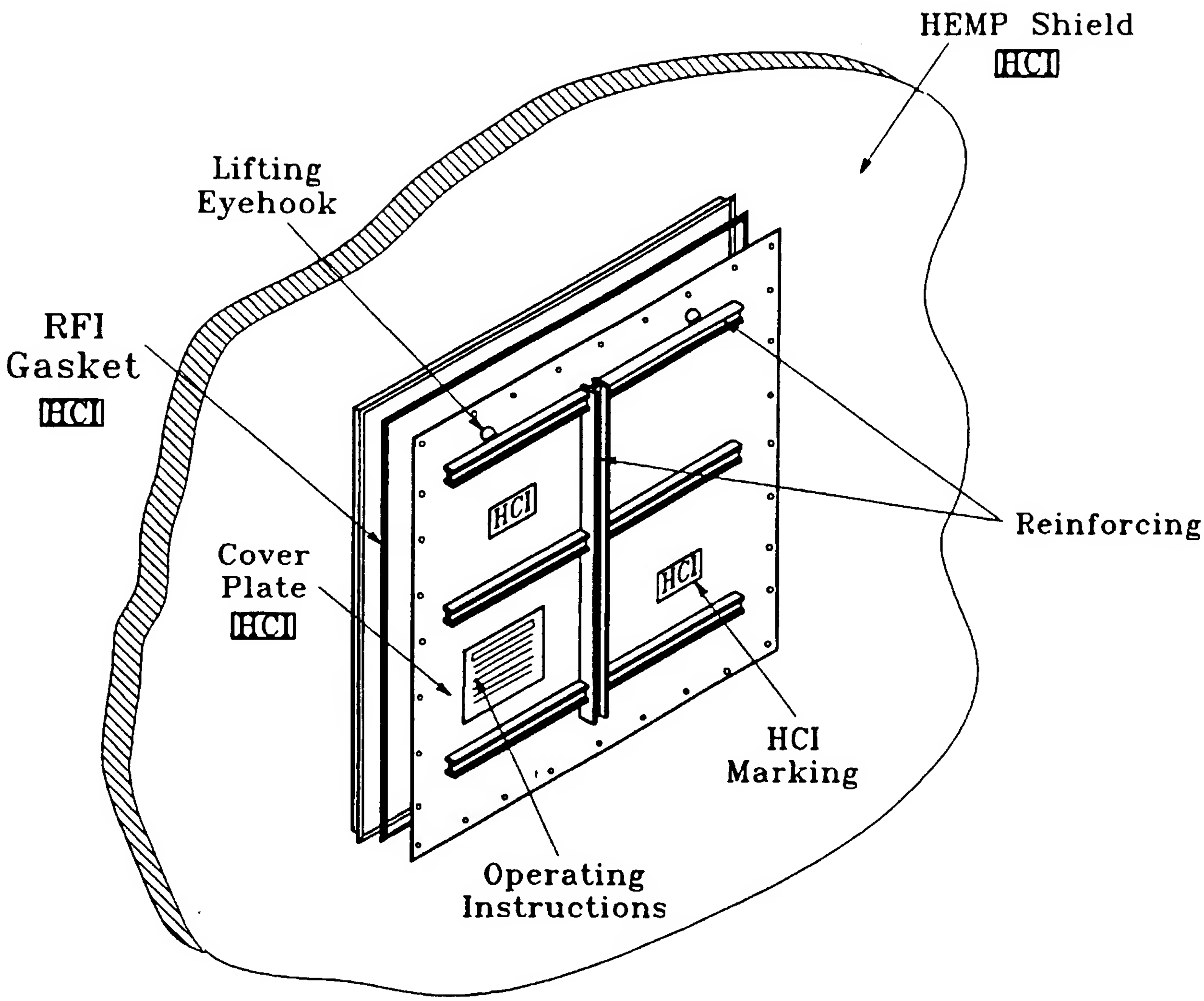
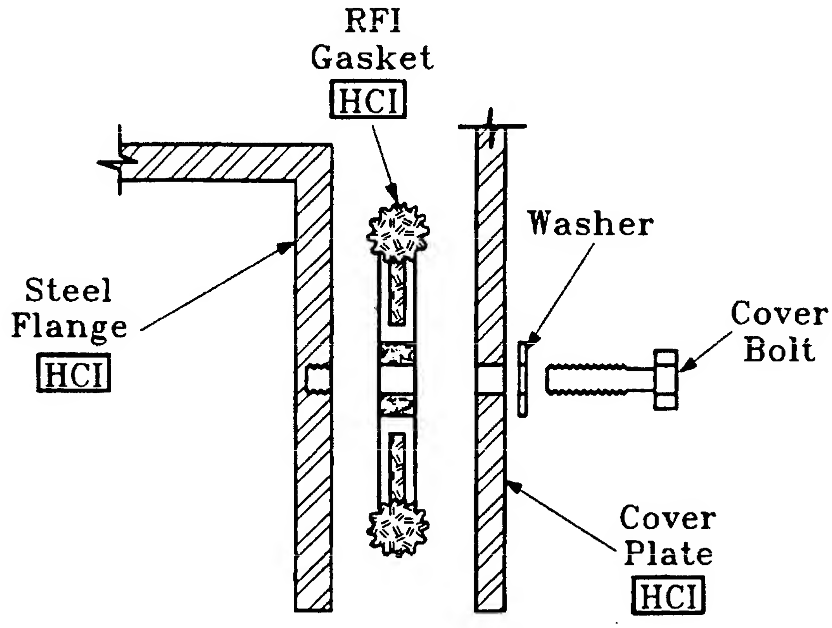


FIGURE 45. Welded equipment access design.

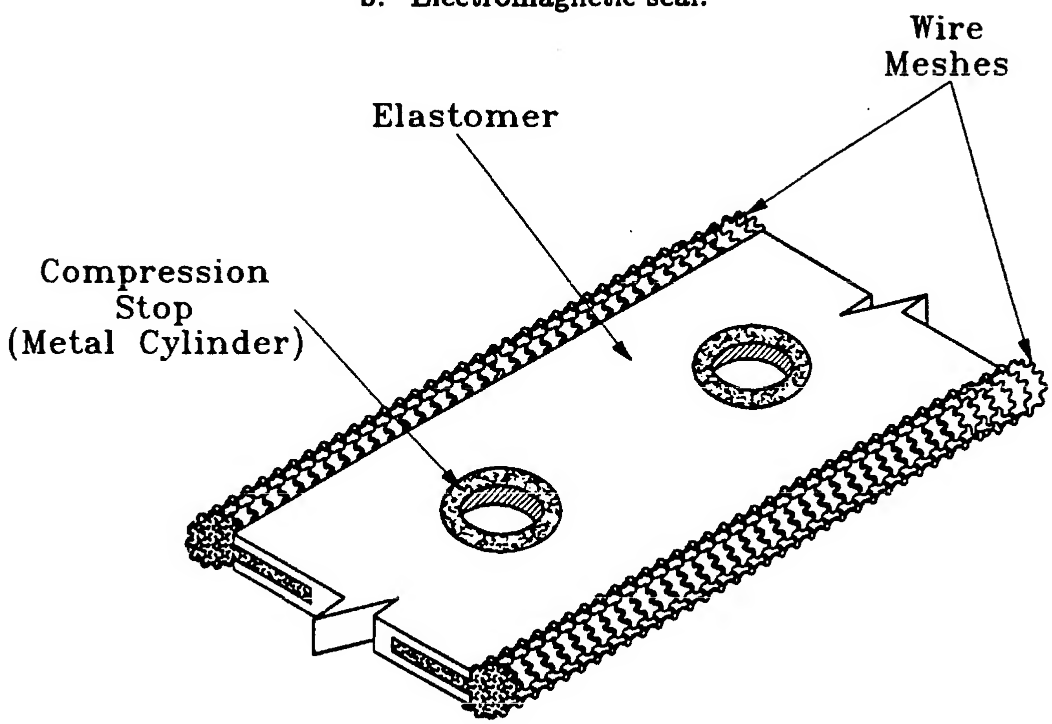


a. Assembly.

FIGURE 46. Gasketed equipment access design.



b. Electromagnetic seal.



c. RFI gasket.

FIGURE 46. Gasketed equipment access design (continued).

Figure 46 shows a section of an rf gasketed seal with a bolted cover, the most common type of mechanical fastener. Important points intended to be made with this drawing include the following:

a. A close bolt spacing, approximately 5 cm (2 in), is necessary to achieve nearly uniform pressure around the entire circumference of the seal. The pressure should be sufficient to hold the surfaces in contact in the presence of deforming stress, shock, and vibration encountered under normal operation in the expected environment.

b. Permanently installed studs or alignment pins should be provided as an aid in positioning the cover before the fasteners are installed.

c. The rf gasket should have high resilience and high conductivity and must be of sufficient thickness and width to allow for expected surface irregularities.

d. Metallic contact surfaces should be machined to a smooth finish and plated, and all nonconductive materials removed.

e. The gasket should be mechanically held in place during disassembly and assembly. It may be mounted on the studs or alignment pins, secured in a groove, or bonded to one metallic surface with conductive adhesive. Spot welding should not be used for this purpose.

f. A thick collar should be provided to ensure that the bolts do not penetrate through the shield.

g. Instructions for installing fasteners, such as bolt torquing requirements, should be prominently displayed on the cover. HCI markings should also be prominently displayed.

h. handles or eye hooks should be welded to the cover to facilitate handling by personnel or by hoists, forklifts, etc.

i. Ridges or braces should be part of large covers to prevent warping or bending.

Equipment access covers, other than welded covers, are required in MIL-STD-188-125 to be protected from exposure to dust and weather. An appropriate weather enclosure must therefore be provided for any mechanically fastened access that is on an outside wall.

9.3.5 Specifications for architectural POEs. HEMP performance for architectural POE protective devices-entryway shields and doors and shielded access covers—is completely defined by specifying the minimum shielding effectiveness. All other requirements

of the standard regarding these items must be reflected either in the facility drawings or the provisions of the specification document.

The drawing package must completely and carefully detail the architectural POE treatments. Hardness critical items (shields, doors, and covers) and hardness critical processes (seam welds, bolt torquing, and conduit electrical bonding in a waveguide entryway) must be identified in accordance with MIL-STD-100 (reference 9-6). Entryway shield geometry and construction details, including explicit welding instructions, should be provialed. Designs for shielded doors and access covers, including auxiliary items such as seal protectors or cycle counters, must be shown in detail. A schematic diagram of the shielded door control, interlock, and alarm circuit should be provided, and the locations of position sensors and control and status panels should be indicated. Installation details must be supplied for all electrical wiring and other conductors in a waveguide-below-cutoff entryway.

Although proper implementation of HEMP protection at architectural POEs relies heavily on the facility drawings, specifications also have a key role. Designers can use the following checklist to ensure that all items have been covered (see also appendix A):

a. Include a specification article which explicitly applies the shielding effectiveness requirement to entryway and equipment access protective treatments.

b. Specify mechanical performance parameters, such as maximum operating force, maximum operating time, and minimum number of cycles between maintenance or failure, which are consistent with the expected usage rates.

c. Completely define the quality control requirements including the following items:

- What tests must be performed
- When and how testing is to be conducted
- Pass/fail criteria
- Documentation of test plans and reports

d. Address maintainability and reliability issues, including the following items:

Ž warranty
- Maintenance procedures
- Maintenance supplies, spares and replacement parts, and special test equipment

9.4 References.

9-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

9-2. "DNA EMP Engineering Handbook for Ground Based Facilities," DNA-H-86-60, Defense Nuclear Agency, 15 November 1986.

9-3. "Code for Safety to Life from Fire in Buildings and Structures," ANSI/NFPA 101, American National Standards Institute, New York, NY.

9-4. Mauriello, A. J., "Development of a doorless access corridor for shielded facilities," IEEE Trans. on Electromag. Compat. 31, No. 3, August 1989.

9-5. "Military Standard – Human Engineering Design Criteria for Military Systems, Equipment, and Facilities," MIL-STD-1472 (effective), Dept. of Defense, Washington, DC.

9-6. "Military Standard - Engineering Drawing Practices," MIL-STD-100 (effective), Dept. of Defense, Washington, DC.

10. MECHANICAL POINTS-OF-ENTRY

10.1 Basic principles. Mechanical POEs allow liquids and gases to pass through the HEMP electromagnetic barrier. They include piping for utilities such as potable water, chilled water, waste water and sewage, fuel, compressed air, and fire suppression agents. Plumbing vents, exhausts for boilers and internal combustion engines, and heating, ventilating, and air conditioning (HVAC) intakes and exhausts are also mechanical POEs. The locations of mechanical penetrations are normally indicated in the architectural drawings, and POE details are shown in the plumbing and mechanical drawings.

Mechanical POEs can occasionally be eliminated by extending the shield around the entire system. A noncritical air compressor could be moved inside the barrier, for example, and this action should be taken if it reduces the number of PO ES. If the equipment is mission-essential and will operate satisfactorily in the protected volume, MIL-STD-188-125 (reference 10-1) requires the extension.

HEMP protection at a mechanical POE is provided with one or more waveguides-below-cutoff. The maximum diameter of a metal WBC with a circular cross-section must not exceed 10 cm (4 in), and the continuous length of the waveguide must be at least five diameters. The maximum length of a side of a square or rectangular WBC is also 10 cm; the continuous length is required to be at least five times the diagonal dimension. For waveguides-below-cutoff with other cross-sectional shapes, the maximum transverse dimension should be limited to 10 cm and the length must be at least five times this largest transverse dimension. All WBCs must be electrically bonded to the HEMP shield at the penetration by welding (this generic usage includes brazing). No dielectric linings are permitted in the waveguide sections.

Exterior and interior pipes and ducts may be coupled to the metal WBC by any appropriate method, so long as the connection is outside the required waveguide length and no conductors enter the WBC section. There are no other HEMP-unique requirements for these couplings.

These requirements apply to both metal and dielectric pipes and ducts. For utilities supplied by a dielectric pipe, the pipe must be cut and coupled to the metal section that serves as the WBC.

The principles of a WBC used as a personnel entryway are discussed in section 9. However, WBCs for mechanical POEs differ from an entryway waveguide in several respects:

a. It is almost always possible to restrict the maximum transverse dimension of the mechanical POE waveguide so that the minimum cutoff frequency f_c is at least 1.5 GHz.

b. Many mechanical WBCs will have a circular, rather than rectangular, cross-section.

c. The fluid that fills the waveguide is not necessarily air. The fluid may have a relative dielectric constant ϵ_r greater than unity and a significant conductivity σ. Effects of these fluid parameters on the waveguide cutoff frequency and attenuation characteristics are discussed below.

Special protective measures, as discussed in section 14, are required if the waveguide dimension must be greater than 10 cm.

The effect of circular cross-section is a slight modification in the equation for low-frequency attenuation A; this relationship for a circular, air-filled waveguide is as follows:

$$A = 30\frac{L}{D}\sqrt{1-\left(\frac{f}{f_c}\right)^2} \quad \text{dB} \tag{11}$$

where L is the waveguide length, D is the diameter (in the same units as L), and f is the frequency.

Reference 10-2 and various electromagnetic texts address the effects of the fill medium dielectric constant and conductivity, and these subjects are briefly discussed here. The waveguide cutoff frequencies are functions of these characteristics of the medium. For example, the lowest cutoff frequency for a dielectrically filled, circular WBC is given by the equation

$$f_c = \frac{0.59\,c}{D\sqrt{\epsilon_r}} \tag{12}$$

where c is the speed of light. Similarly, the lowest cutoff frequency for a dielectrically filled, rectangular waveguide (see section 9) is inversely proportional to the square root of the relative dielectric constant of the interior medium. The relative dielectric constants of nearly all gases are between unity and 1.02 at room temperature and near-atmospheric pressure. Table VII lists the approximate room temperature dielectric constants for several common liquids.

Equation 12 indicates that a piping penetration WBC for water (ϵ_r = 78) must be less than 1.34 cm (0.53 in) in diameter for a cutoff frequency greater than 1.5 GHz. When the interior water pipes are dielectric, this reduction in the maximum transverse dimension of the waveguide is required. If the liquid in the protected volume is confined within a closed

TABLE VII. Dielectric constants of liquids.

Liquid	Relative Dielectric Constant
Benzene	2.3
Ethanol	24.
Ethelene glycol	37.
Octane	1.9
Refrigerant 12	2.1
Transformer oil	2.2
Water	78.

metal piping system, however, the pipe blocks the leakage path and the reduction in size is not necessary. For this reason, metal piping should be used inside the electromagnetic barrier for all penetrating liquids.

Another effect of fluid conductivity, when the fluid is in intimate contact with the metal walls of the WBC, is to increase the waveguide attenuation at all frequencies. However, a coaxial geometry will be created if the fluid is dielectrically isolated from the waveguide walls; this is the reason that MIL-STD-188-125 prohibits dielectric linings in piping WBCs.

10.2 MIL-STD-188-125 requirements.

5.1.5.1 <u>HEMP protection for mechanical POEs.</u> HEMP protection for mechanical POEs, including piping and ventilation penetrations through the facility HEMP shield, shall be provided with waveguide-below-cutoff techniques. As a design objective, the number of piping POEs should be constrained to fewer than 20 and the number of ventilation POEs should be constrained to fewer than 10.

5.1.5.1.1 <u>Quality assurance for mechanical POE protective devices.</u> All welded and brazed seams and joints for installation of mechanical POE protective devices, including those for piping and ventilation penetrations, shall be monitored under the program of in-progress inspection of welded and brazed seams and joints (see 5.1.9.4.1).

5.1.5.1.2 Acceptance testing for mechanical POE protective devices. Acceptance testing for mechanical POE protective devices, including those for piping and ventilation penetrations, shall be conducted using shielding effectiveness test procedures of appendix A.

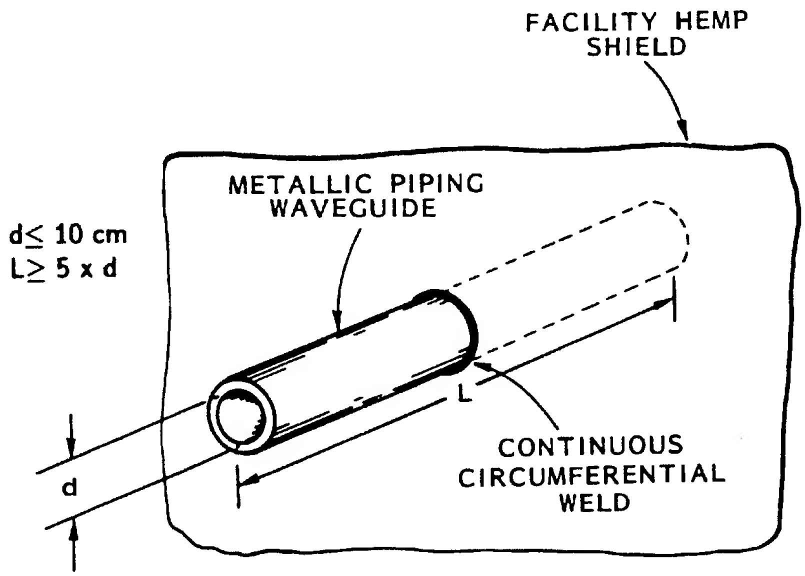
5.1.5.2 Metallic piping POEs. Metallic piping shall penetrate the facility HEMP shield as a pipe section which is configured as a single waveguide-below-cutoff or a waveguide-below-cutoff array (figure 3). Dielectric hoses or pipes shall be converted to metal piping before penetrating the shield. The presence of the protected piping POE shall not degrade shielding effectiveness of the facility HEMP shield below the minimum requirements of figure 1.

5.1.5.2.1 Metallic piping waveguide dimensions. The inside diameter of a single waveguide-below-cutoff and each of the transverse cell dimensions in a waveguide-below-cutoff array shall not exceed 10 cm (4 in), except where a special protective volume will be established (see 5.1.8.9.1). The length of the waveguide section shall be at least jive times the inside diameter of a single waveguide-below-cutoff or at least jive times the transverse cell diagonal dimension in a waveguide-below-cutoff array.

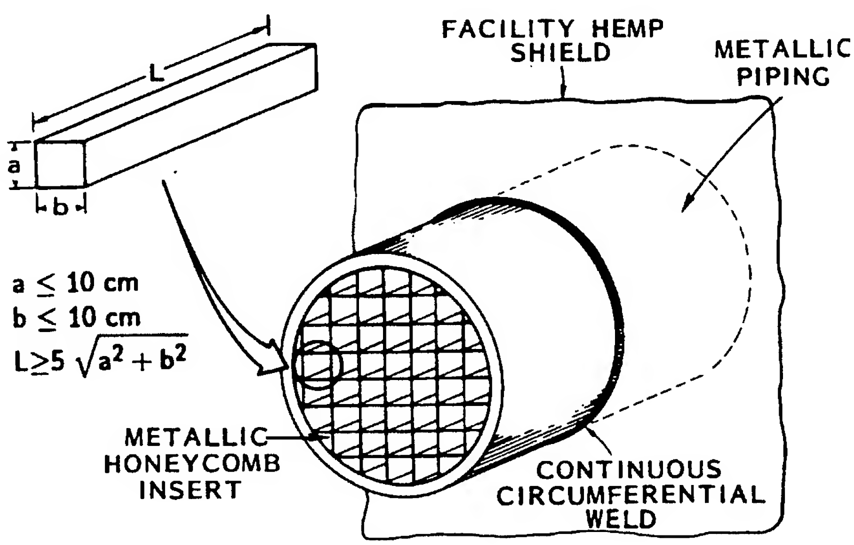
5.1.5.2.2 Metallic piping waveguide construction. All joints and couplings in the waveguide Section shall be circumferentially welded or brazed, and the waveguide-below-cutoff shall be circumferentially welded or brazed to the facility HEMP shield at the POE. Cell walls of a waveguide-below-cutoff array shall be metallic, and there shall be continuous electrical bonds at all intersections and between the cell walls and the waveguide wall. No dielectric (glass, plastic, etc.) pipe lining shall be permitted in the waveguide section. External and internal piping shall be connected at the ends of the waveguide Section; no HEMP-unique requirement apply to these couplings.

5.1.5.3 Ventilation POEs. Ventilation ducts shall penetrate the facility HEMP shield in a Section of metallic ducting which is configured as a waveguide-below- cutoff array panel (figure 4). The presence of the protected ventilation POE shall not degrade shielding effectiveness of the facility HEMP shield below the minimum requirement of figure 1.

5.1.5.3.1 Waveguide array dimensions. Each of the transverse cell dimensions of the waveguide-below-cutoff array shall not exceed 10 cm (4 in). The length of the waveguide shall be at least five times the transverse cell diagonal dimension.



a. Single waveguide-below-cutoff.



b. Waveguide-below-cutoff array.

FIGURE 3. Typical waveguide-below-cutoff piping POE protective devices.

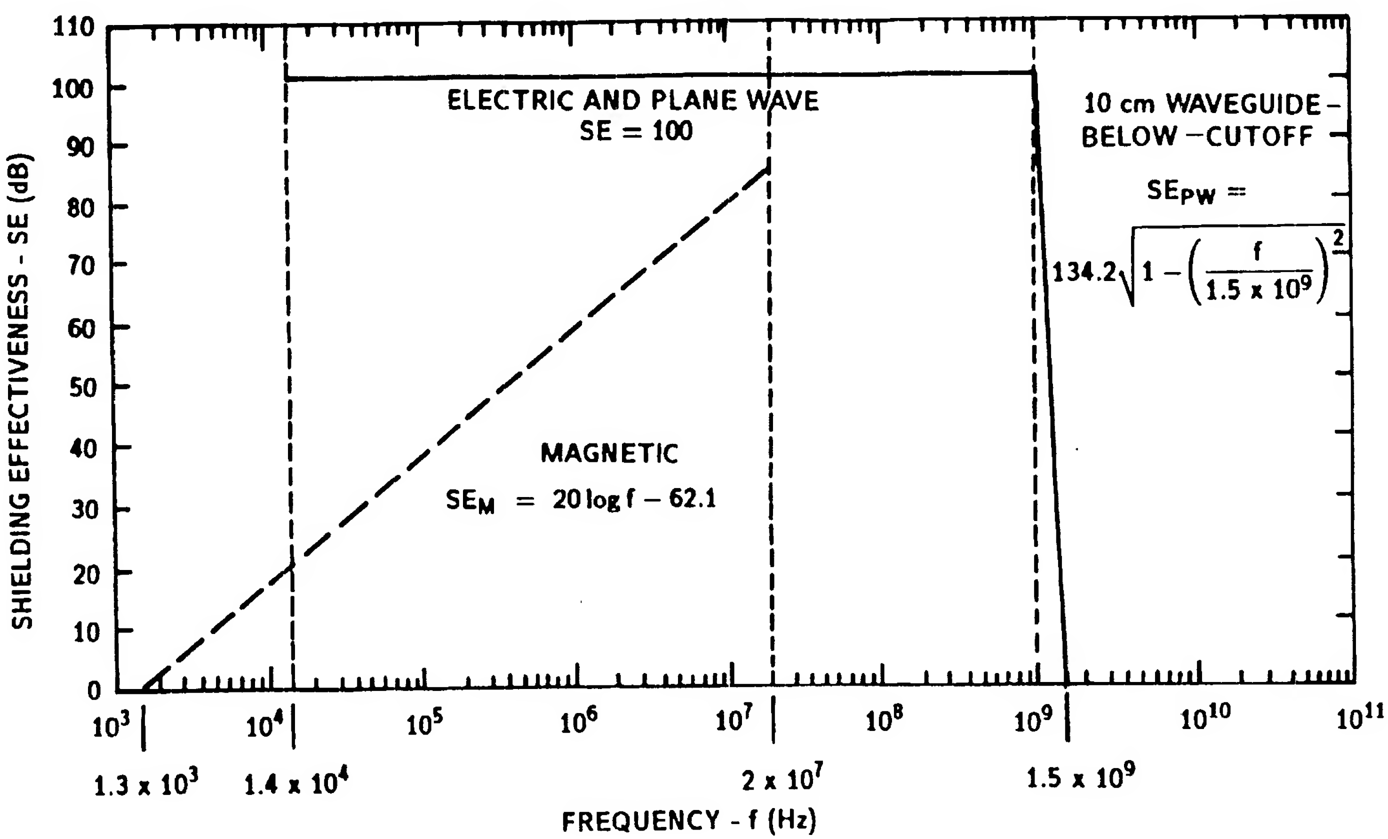
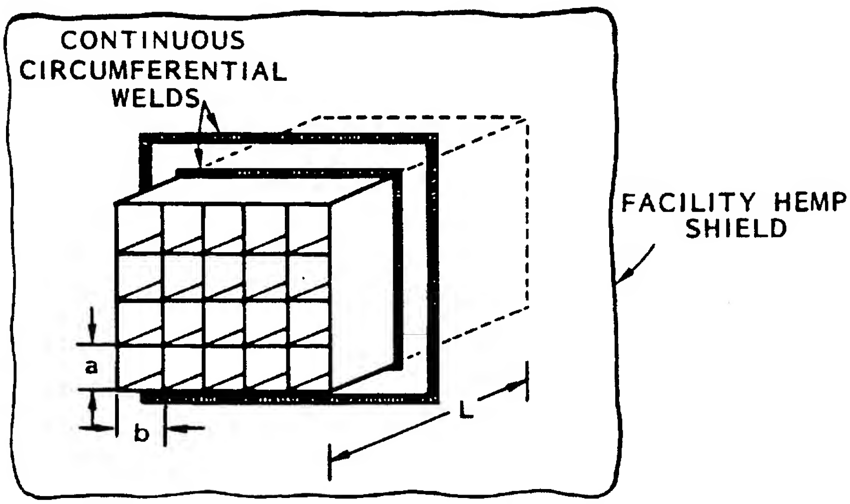


FIGURE 1. *Minimum HEMP shielding effectiveness requirements (measured in accordance with procedures of appendix A).*



$a \leq 10$ cm
$b \leq 10$ cm
$L \geq 5\sqrt{a^2 + b^2}$

FIGURE 4. Typical waveguide-below-cutoff array ventilation POE protective device.

5.1.5.3.2 Waveguide array construction. The waveguide-below-cutoff array panel shall be circumferentially welded or brazed to the facility HEMP shield at the POE. Cell walls shall be metallic and there shall be continuous electrical bonds at all intersections and between the cell walls and the duct wall. No conductors shall be permitted to pass through the waveguide.

10.3 Applications.

10.3.1 General guidance. Mechanical POEs fall into two broad categories: piping and HVAC penetrations. The POE protection must be designed to preserve the shielding effectiveness of the barrier, while performing the mechanical service that the POE is intended to provide.

Early in the design of a HEMP-protected facility, consideration involving mechanical POEs include the following determinations:

a. What systems are involved.

b. What types of penetrations are required.

c. Whether they are all needed and how their number might be reduced; the use of different mechanical systems from those originally planned, for example, can eliminate penetrations.

d. Where the penetrations are located; it is strongly encouraged that piping POEs be located in the penetration entry area.

Early planning can often reduce the number of mechanical POEs. For example, a downspout for a roof drain will be a mechanical POE if the downspout is allowed to penetrate the barrier. Similarly, a mechanical designer may find it convenient to route an HVAC duct through the protected volume, creating a POE, even though the duct does not serve this volume. In these instances, the downspout and the duct should be routed outside the shield and the POEs eliminated.

Other approaches for minimizing POEs include the use of different mechanical equipment that requires fewer penetrations and relocating equipment. Whenever there are parts of a mechanical system both inside and outside the barrier, relocation should be considered, in combination with the constraint that mission-critical equipment must be placed in the protected volume.

All remaining mechanical POEs are to be HEMP protected using waveguide-below-cutoff principles. The inside diameter of a circular WBC or sides of a rectangular WBC must be limited to 10 cm (4 in), in accordance with MIL-STD-188-125. The waveguide or WBC section is required to be electrically continuous for a length L, which must be at least five times the diameter or transverse diagonal dimension of the opening. No dielectric pipe lining is allowed in the waveguide section.

Dielectric pipes may not penetrate the barrier. A dielectric pipe must be converted to a metallic WBC which passes through the barrier. For reasons discussed in subsection 10.1, metal piping systems are also recommended in the protected volume for all penetrating liquids.

The above constraints pose no problem for most applications, although they may impact the design. For example, the WBC panel in an air duct may cause some reduction in the air flow. Increasing the size of the duct and the WBC panel will compensate for this effect.

It is desirable to locate the piping penetrations at the PEA, even when this causes an increase in the lengths of the piping runs. An exception to this general rule is provided

in MIL-STD-188-125, however, when the length of the external pipe run is less than 10 m (32.8 ft).

10.3.2 Piping penetrations. Piping penetrations are normally identified and described by their functions. Examples include potable water lines, chilled water supply and return lines, sprinkler pipes, drains and waste water lines, fuel lines, compressed air lines, and diesel or turbine generator and boiler exhausts. All of these POEs are treated with sections of metallic piping that are configured as WBC protective devices. The general methods of treatment are discussed first, and unique requirements for particular types of piping POEs are then addressed in succeeding subsections.

Figure 47 shows an isometric drawing of a piping penetration weld panel with four WBCs and a cross section of a single protected piping POE. The thickness of the steel weld panel is 6.4 mm (0.25 in). This thickness is recommended where a long intersite pipe, such as a base service water line, can deposit a large HEMP-induced transient on the barrier. Holes are cut or drilled in the plate to allow the waveguide sections to be inserted, and the WBCs are then circumferentially welded to the plate.

Each of the WBCs must satisfy the maximum inside diameter and minimum continuous length requirements (see section 14 for pipes larger than 10 cm inside diameter). Couplings in the waveguide section must be metallic and circumferentially welded. Although the drawing indicates approximately equal lengths on each side of the plate, this is not a requirement. The length L adjacent to the circumferential weld may be inside the protected volume, outside the barrier, or a combination of inside and outside.

HEMP requirements do not govern the construction of couplings and pipes that are beyond L and are not part of the waveguide section. The couplings beyond L may therefore be welded, threaded, or bolted, and they may be metallic or dielectric. Similarly, piping that is not part of the waveguide section may be metallic, dielectrically lined metal, or dielectric and is not limited to an inside diameter of 10 cm. Couplings outside the required length L are used to convert dielectric pipes and hoses or metal pipes constructed of a material other than a weldable steel to the steel WBCs.

The weld plate assembly can be fabricated in the shop. Spacing between the WBCs is chosen to provide sufficient access for performing the welds and is not determined by HEMP design considerations. The plate is then installed, with appropriate mechanical support to prevent excessive stress on the barrier, by circumferentially welding it to the HEMP shield.

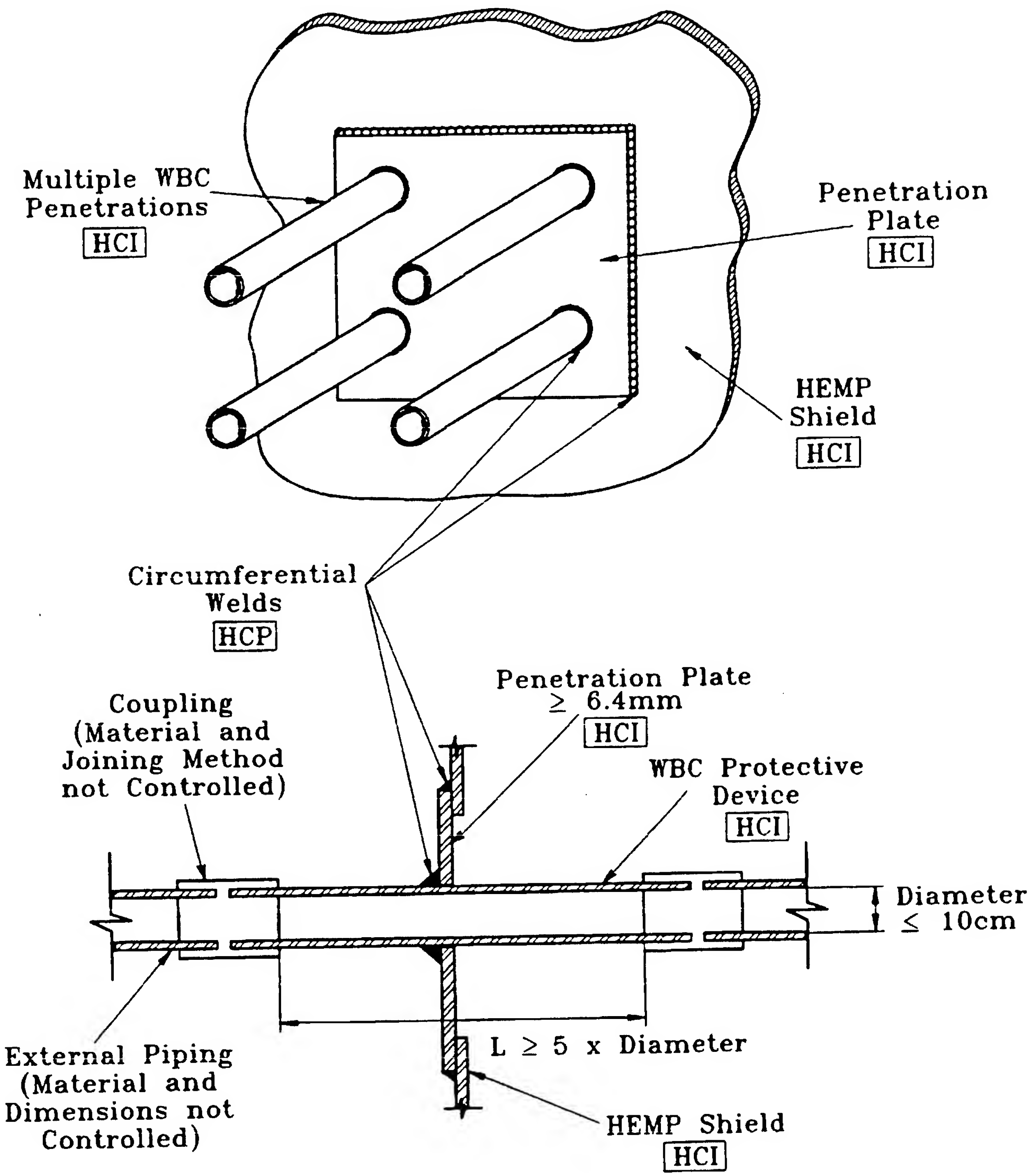


FIGURE 47. Weld plates with WBC protective devices.

The use of a weld plate is strongly recommended as a general practice for installing the piping WBC protective devices, although such a plate is not a requirement of the standard. The weld plate enhances the mechanical strength of the shield in the area where the piping connections are likely to cause increased mechanical stresses. The ability to shop fabricate the assembly is also a significant advantage. If a weld plate is not employed, however, the piping WBCs can be circumferentially welded directly to the HEMP shield.

Another variation on the treatment of a piping POE is the use of a sleeve as shown in figure 48. The sleeve is slightly larger in diameter than the penetrating pipe to be inserted, but complies with the 10-cm maximum transverse dimension and the minimum length requirements. The sleeve acts as a waveguide-below-cutoff before the piping system is in place and allows the shield to be constructed and tested. The pipe can then be installed at a later time by circumferentially welding it to the sleeve at one end (or at both ends). Note that the welded joint between the pipe and the sleeve is hardness critical;

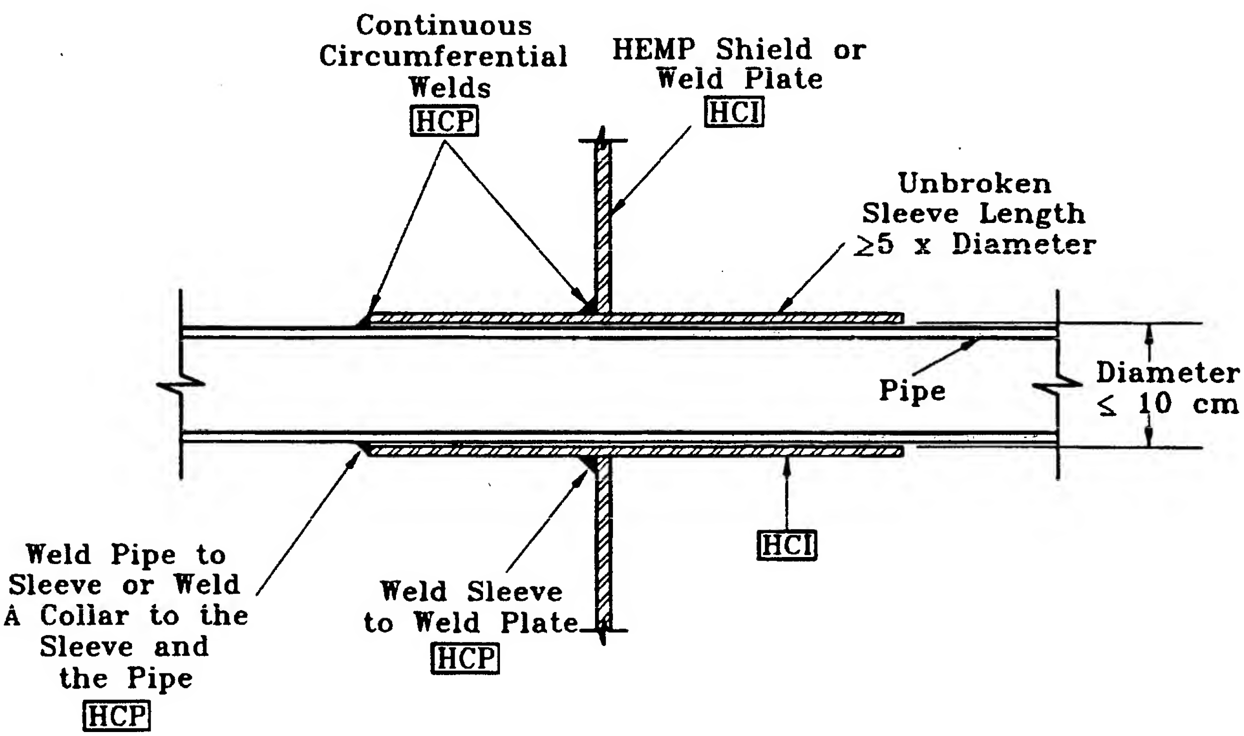


FIGURE 48. Pipe penetration through a WBC sleeve.

without this circumferential weld, the effectiveness of the penetration treatment would be lost.

10.3.2.1 Chilled water penetrations. Chilled water pipes are a special category of piping penetration because the fluid and pipe wall temperature can be substantially less than that of the surrounding air. This situation can lead to condensation and a high rate of corrosion.

The basic design of a chilled water penetration WBC and weld plate is that described in 10.3.2. However, pipe insulation should be provided as shown in figure 49 to reduce condensation and to limit undesirable heat transfer to the water. The insulation must necessarily be interrupted at the weld panel, but it should be installed to fit as closely as possible against the plate.

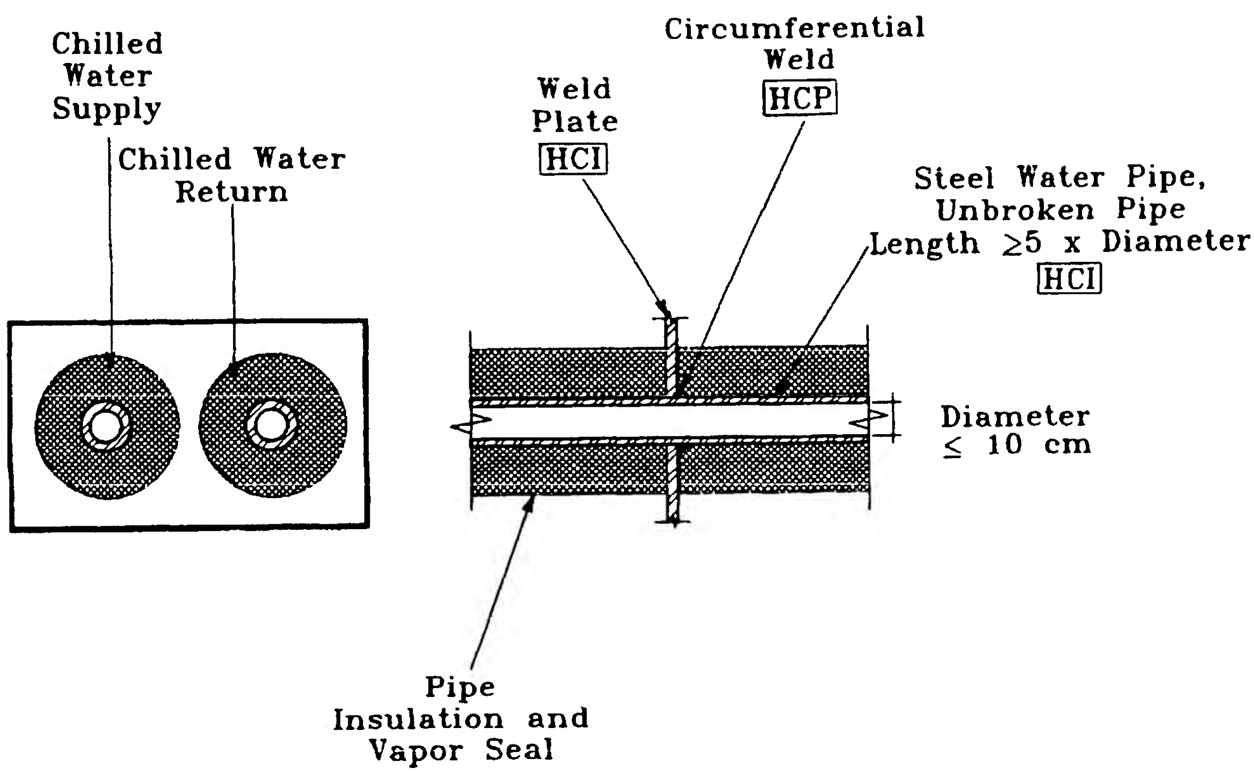


FIGURE 49. Chilled water pipe penetrations.

10.3.2.2 Sprinkler pipe penetrations. Sprinkler pipe penetrations must comply with applicable fire safety codes, as well as the HEMP POE protection requirements. Where safety codes require additional penetrations for alarm signaling, such as a flow-actuated water-motor gong, the additional penetrations must also be HEMP protected in accordance with MIL-STD-188-125.

10.3.2.3 Copper piping systems. For various reasons, some piped fluid systems employ copper pipes that must be connected to the steel WBC sections. The transition must be made in a manner which does not promote galvanic corrosion (see section 15). The preferred approach is to convert from copper to steel with an intervening dielectric piping section. Another approach is to use a series of material transitions to achieve galvanic compatibility, such as first converting from copper to brass and then from brass to steel. These conversions should be made outside the required continuous length L (see figure 47).

Similar approaches are used to convert from pipes constructed of other metals.

10.3.2.4 Drain lines. Drainage and drain lines are addressed here as a special case because common installation practices are not suitable for a HEMP-hardened facility. In a conventional building, water is sometimes allowed to drip onto the concrete floor to be collected and discharged through floor drains. Furthermore, the drain lines are often constructed of plastic, wrought iron, or other nonweldable materials. Neither of these practices is allowable in a HEMP shielded enclosure.

In order to minimize corrosion, water should not be permitted to drain onto the HEMP shield. A “drip pan” should be provided under any equipment where water leakage or condensation is expected. The discharge from the drip pan is then piped to a drain line, as indicated for an air conditioning unit in figure 50. The drain line must be constructed of a steel suitable for welding to the HEMP shield, and it must be configured as a piping waveguide-below-cutoff POE protective device. If a separate “cleanout” penetration is required, as indicated by the dashed lines in figure 50, this POE must also have protection that satisfies the requirements for a piping WBC. Small-cell honeycomb inserts should not be installed in drain lines because they clog easily.

When it is not practical to confine the leakage with a drip pan, such as in a shower room or lavatory within the shield, a concrete slab with floor drains may be used. A vapor barrier should be provided between the floor shield and the slab, and a water sealant should be applied after the concrete has dried. Drains from the sinks and toilets are protected at the penetrations in the manner illustrated by figure 50.

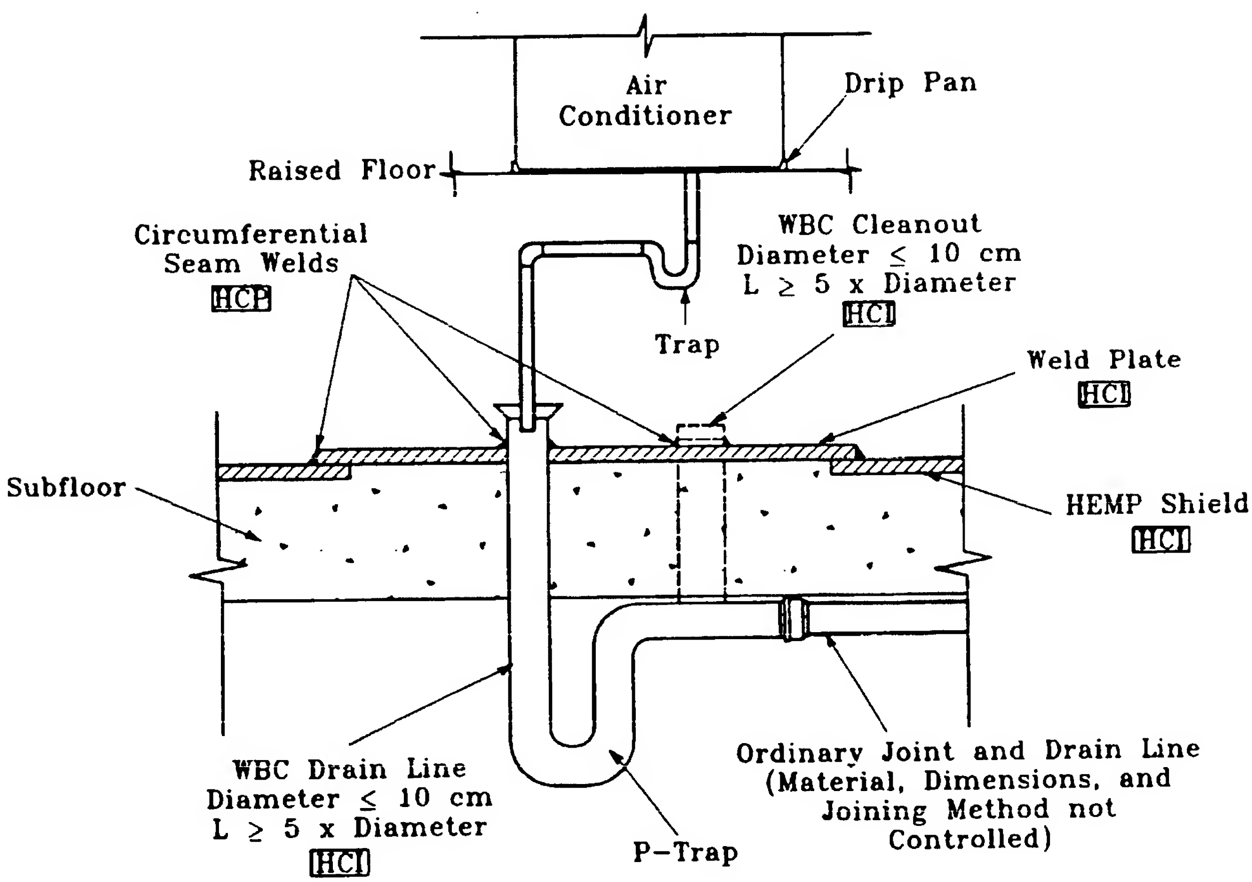


FIGURE 50. Computer air conditioner drain line penetration details.

An alternate treatment of waste water is to collect the drainage in a sump that is not part of the shield. The waste can then be pumped or blown with compressed air out of the building.

10.3.2.5 Generator and boiler exhausts. The unique requirements for generator and boiler exhaust penetrations are principally related to the high temperature of the gases being discharged. The design must accommodate the thermal expansion which occurs as the generator or boiler goes from a cool, nonoperating state to a condition producing hot exhaust gases. Heat conduction from the exhaust stack wall to the shield must also be controlled to minimize thermal stresses on the shield.

The equipment, particularly a diesel generator, may also produce significant vibration that should not be transmitted to the shield. Finally, the inside diameter of the exhaust pipes is sometimes required to be greater than 10 cm (4 in).

One design for a diesel exhaust through the wall of the barrier is shown in figure 51. Most of the thermal expansion in the length of the exhaust pipe and most of the vibration are taken up by the metal bellows. The angled flashing, which is circumferentially welded to the stack and to the oversized pipe sleeve, permits expansion in both length and diameter. Rigid insulation where the exhaust passes through the barrier serves as both a limiter for transverse vibrations and a heat insulator. The flashing and sleeve configuration also increases the length of the heat conduction path and thereby limits heat transfer to the shield.

When the exhaust pipe must be larger than 10 cm (4 in) in diameter, limitations on the maximum transverse dimension must be met by providing a metallic honeycomb insert. The insert is installed at the outer end of the pipe, where the exhaust gas temperature is lowest. One method of fabricating the waveguide insert is to weld several steel tubes into steel end plates, similar to the installation of boiler and heat exchanger tubes. The illustration shows a waveguide assembly constructed from round pipes; square metal tubing may also be employed. In either case, the individual tubes must satisfy the maximum transverse dimension and minimum length requirements of MIL-STD-188-125. The use of a waveguide section such as this is preferred over establishing a special protective barrier inside the protected volume with the closed exhaust piping.

Figure 52 illustrates a similar design for a boiler exhaust stack through the roof. This design accommodates somewhat less longitudinal expansion because boiler exhaust gas temperature is generally less than that of a diesel. The drawing also shows one of three galvanized steel cables for mechanical support to protect the pipe in high wind conditions.

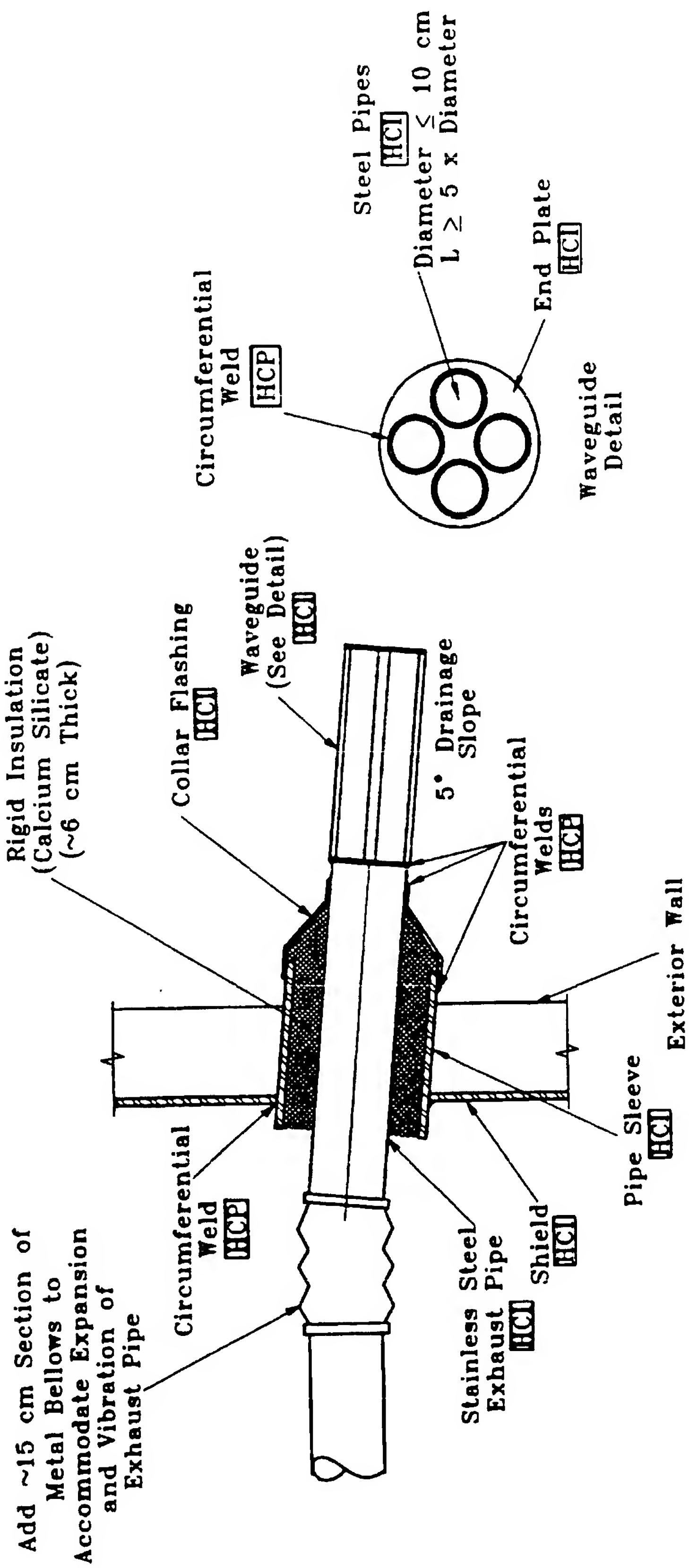


FIGURE 51. Generator exhaust penetration.

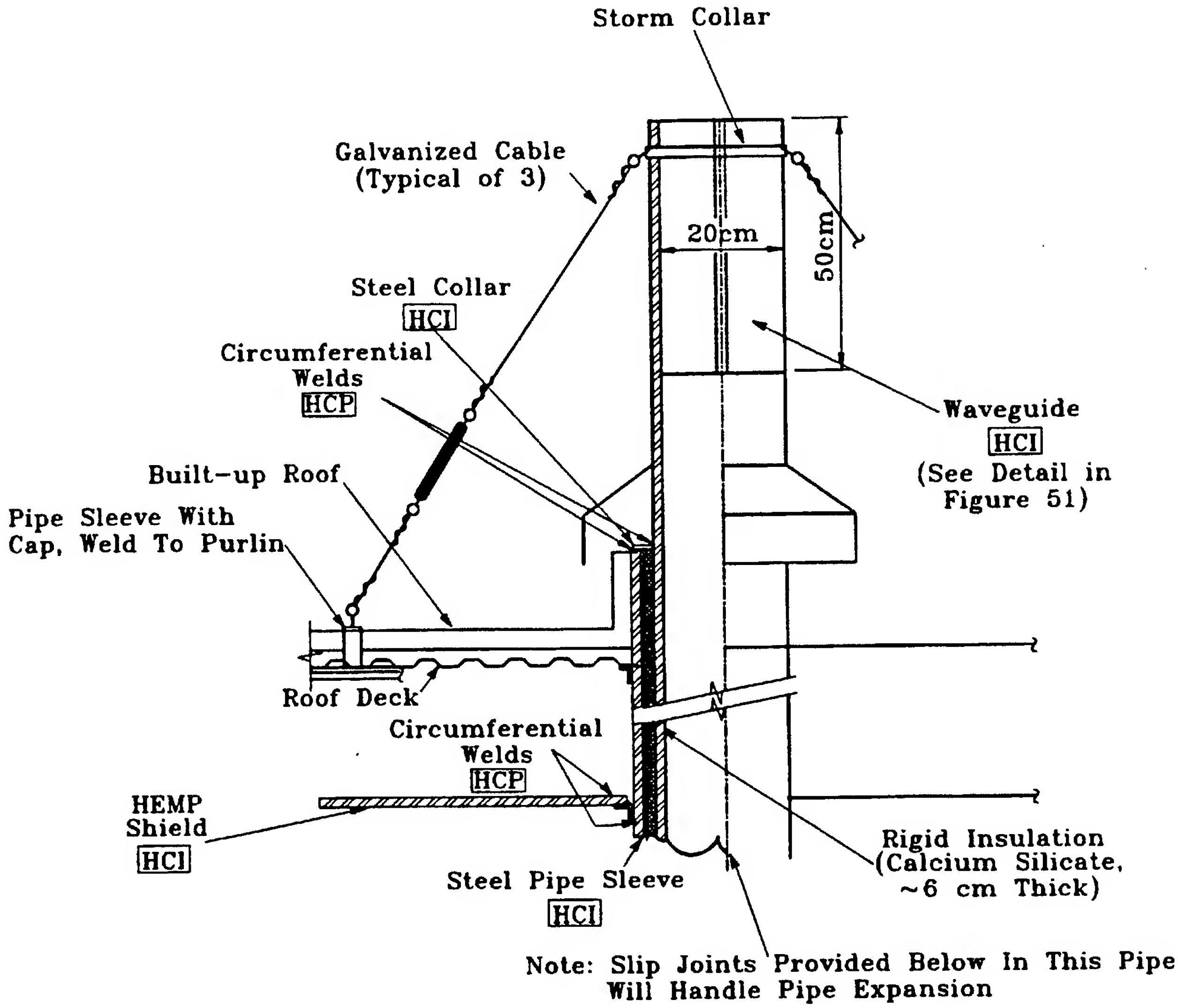


FIGURE 52. Boiler exhaust through the ceiling shield.

10.3.3 Heating, ventilating, and air conditioning system penetrations. Ventilation penetrations are similar to piped utility POEs in that they must permit fluid flow through the electromagnetic barrier. In general, however, the overall dimensions of the aperture required for an HVAC air passage cannot be reasonably constrained within the 10-cm transverse dimension limit for a single waveguide-below-cutoff. Thus, the air duct by itself cannot serve as the waveguide. The POE treatment required by MIL-STD-188-125 in this situation is a waveguide-below-cutoff array.

A WBC array divides a single large aperture into many small apertures, each protected with an individual WBC that does satisfy the MIL-STD-188-125 requirements for maximum transverse dimension and minimum length. Two designs to produce and protect these small aperture POEs—a welded WBC array and a commercial honeycomb WBC array—are discussed.

10.3.3.1 Welded WBC ventilation panel. The preferred POE protective treatment for a ventilation penetration is to shop-fabricate a WBC array panel as shown in figure 53. The panel consists of a matrix of waveguide cells welded to the HEMP shield.

There are various methods for constructing the waveguide array. One method is to build up the assembly from lengths of square metal tubing, as illustrated in figure 54. At one end, the tubes must be joined together with continuous seam welds. The outer tubes in the array must also be longitudinally seam welded, at least to the point where the steel frame is attached. Tack welds, which are not hardness critical, can be used for other longitudinal joints as required by mechanical considerations.

Another technique is to create the square matrix with interlocking metal sheets of the type shown in figure 55. For this technique to be effective, cell walls must be continuously bonded at all intersections. This can be accomplished by seam welding each individual joint or by tack welding and metal plating the entire assembly using a hot-dipped process.

The completed WBC array panel is then circumferentially welded into the HEMP shield. A simple installation is shown in figure 56, and figure 57 illustrates the array sloped to minimize entry of wind-driven rain and snow. Louvers that are operated from inside the protected volume should be placed at the inner end of the waveguides so that the operating mechanisms do not require POEs. A bird and insect screen is normally installed at the outer end to prevent nesting.

10.3.3.2 Commercial honeycomb WBC ventilation panel. Electromagnetic protection at a ventilation POE can also be provided with a panel that uses commercially available honeycomb material to form the array of WBCs. The commercial honeycomb

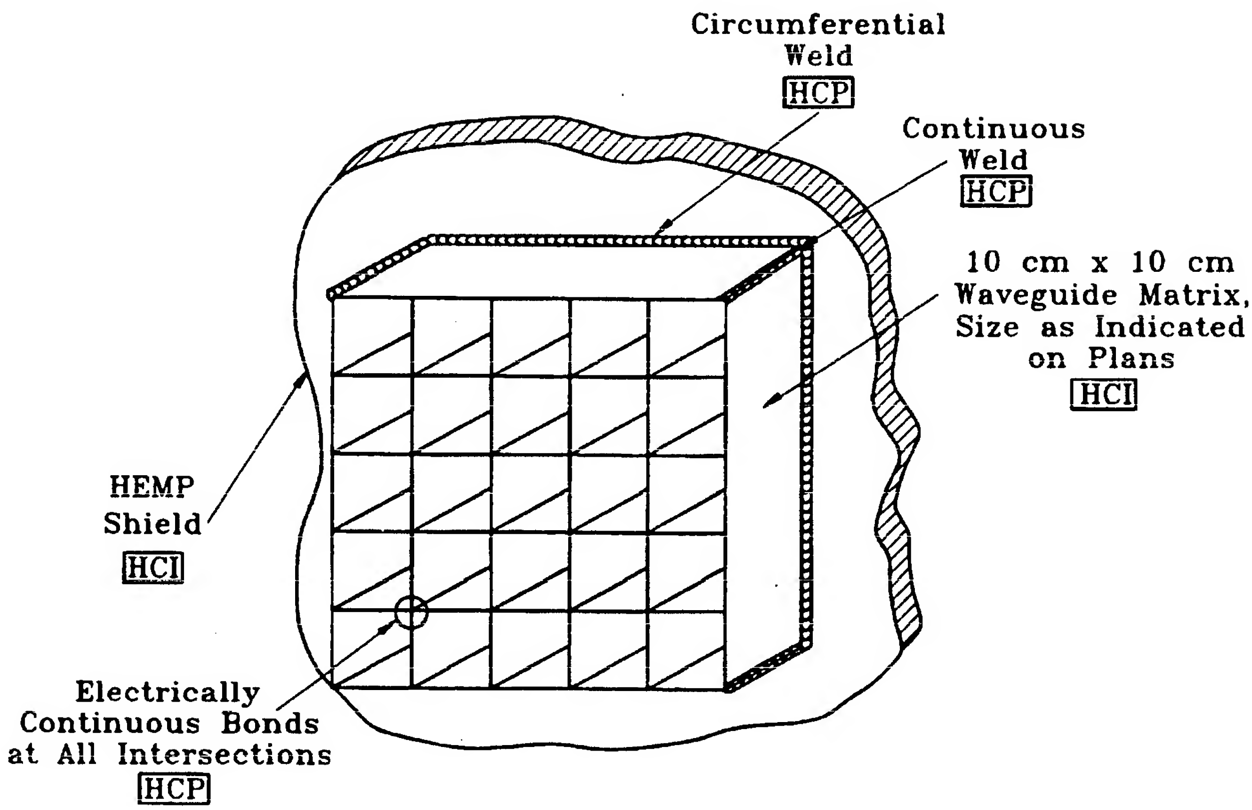


FIGURE 53. Welded waveguide array panel.

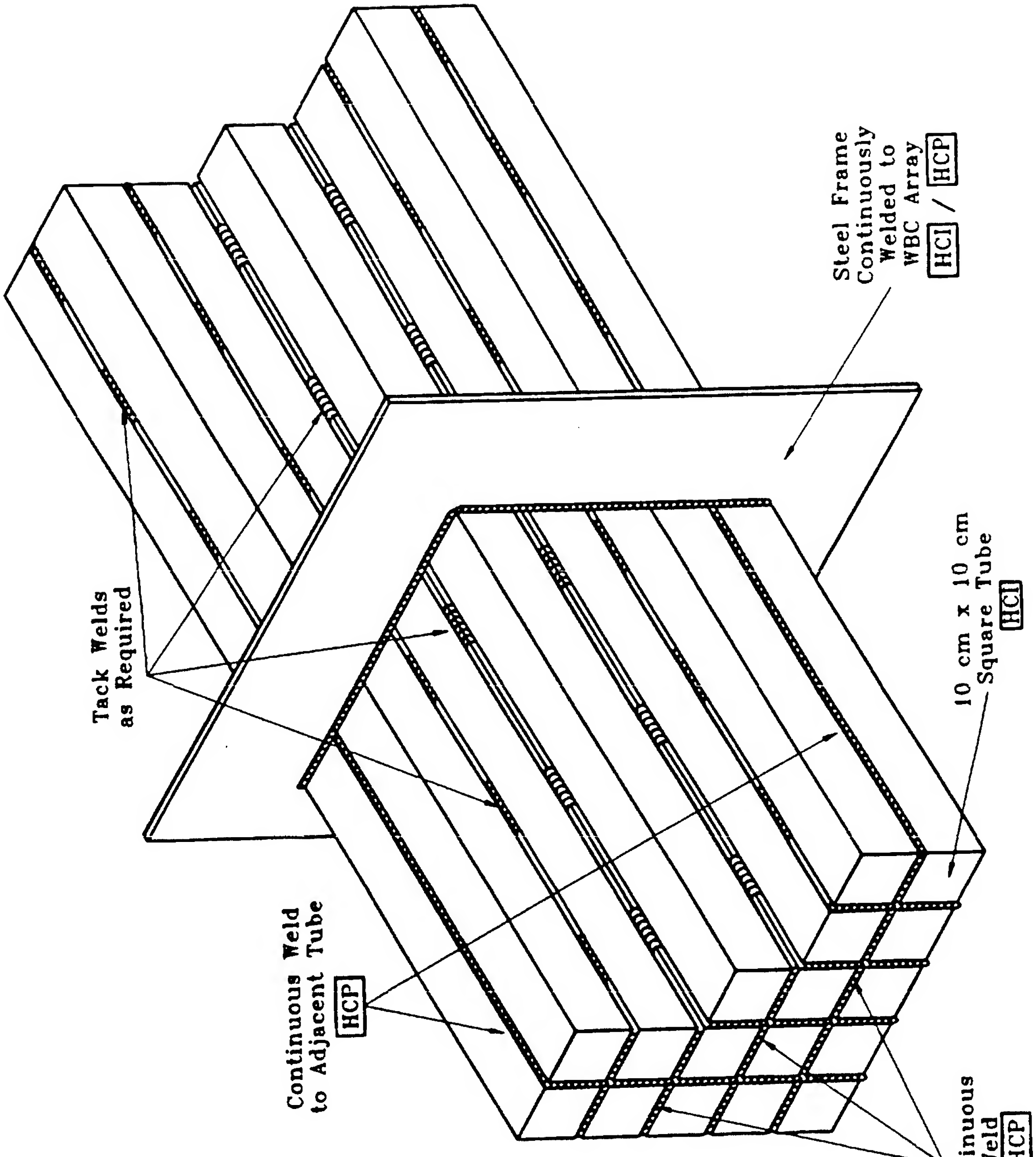


FIGURE 54. Welded WBC panel assembled from square metal tubes.

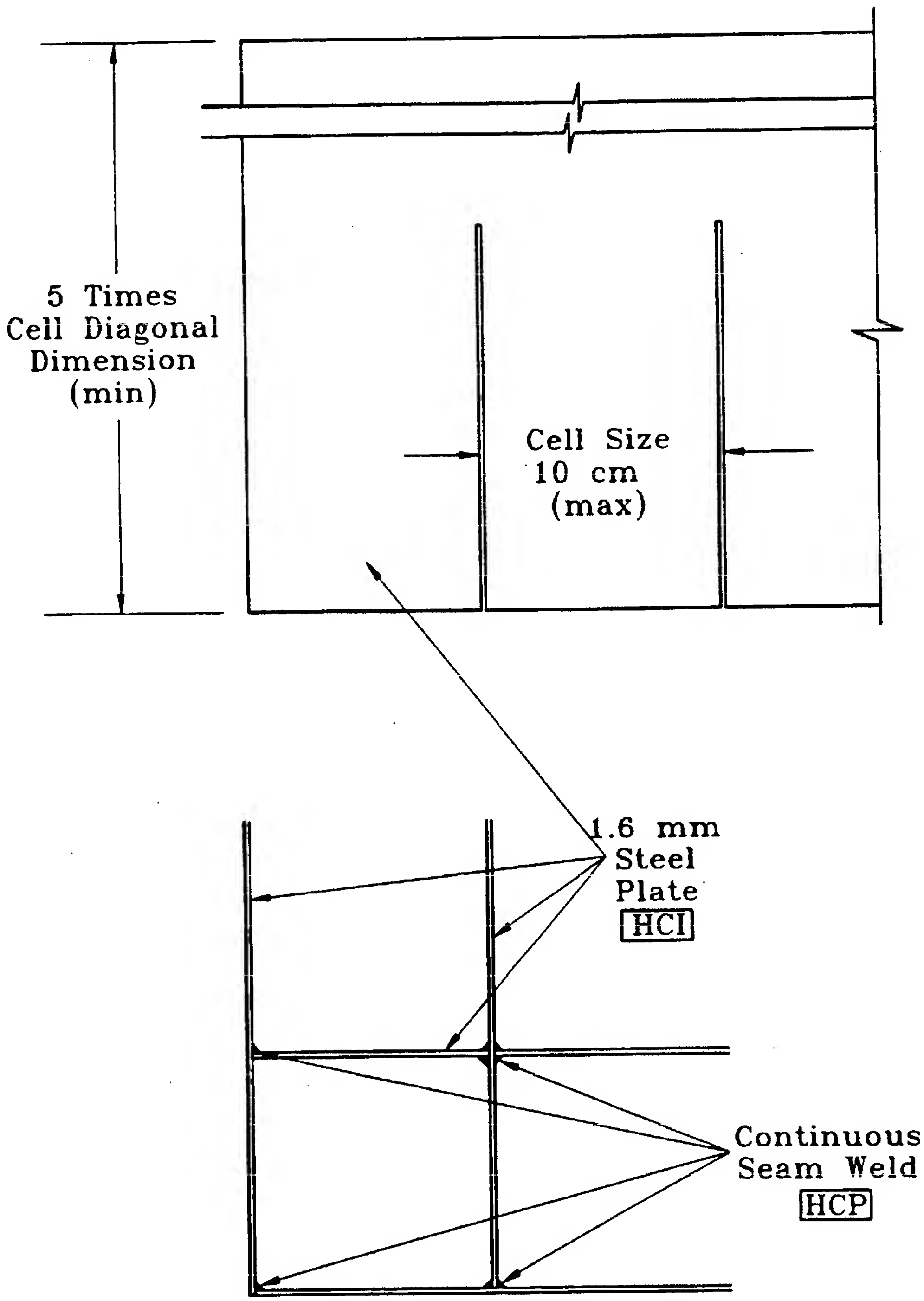


FIGURE 55. Waveguide matrix detail.

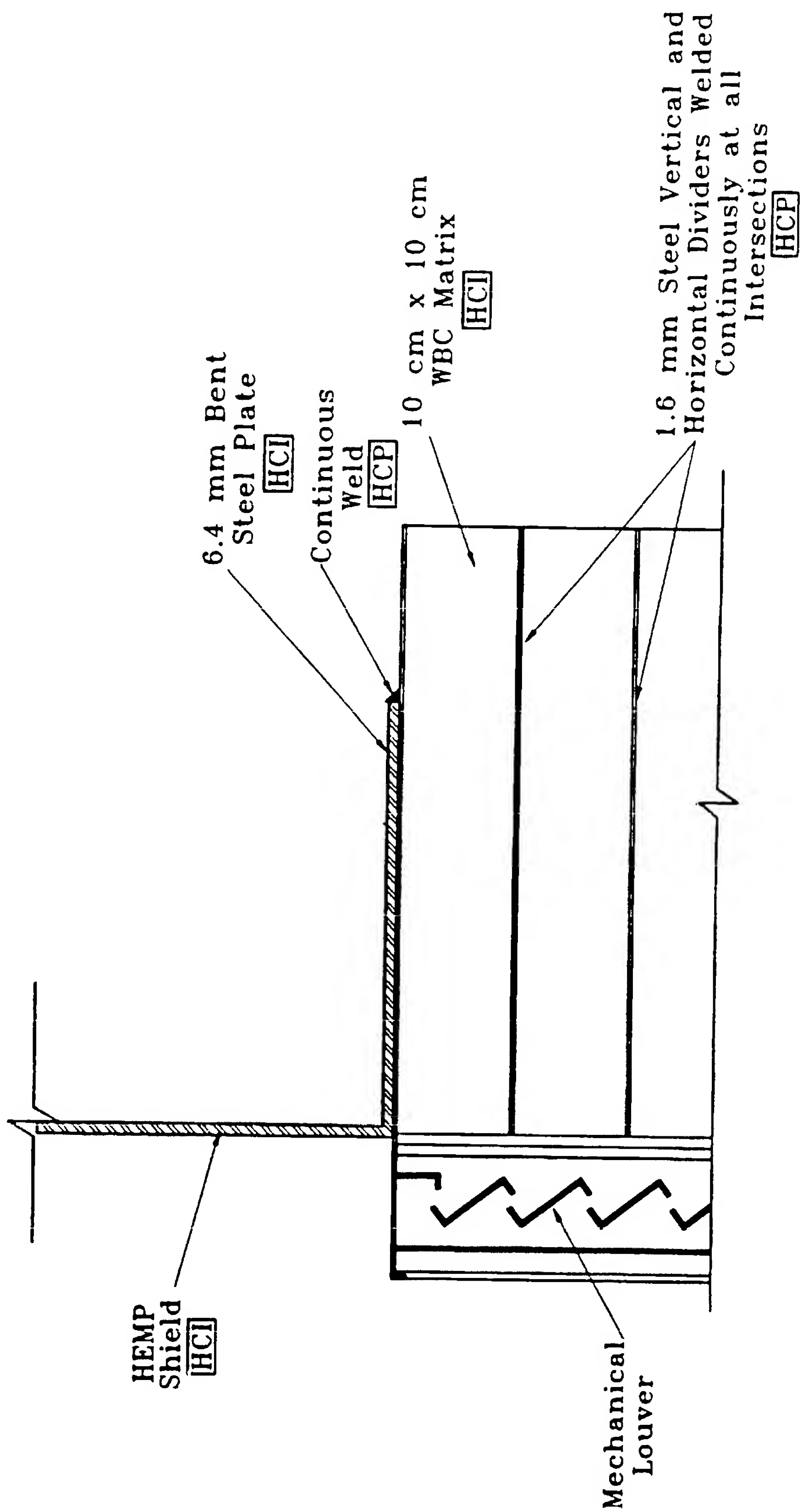


FIGURE 56. Installed WBC array.

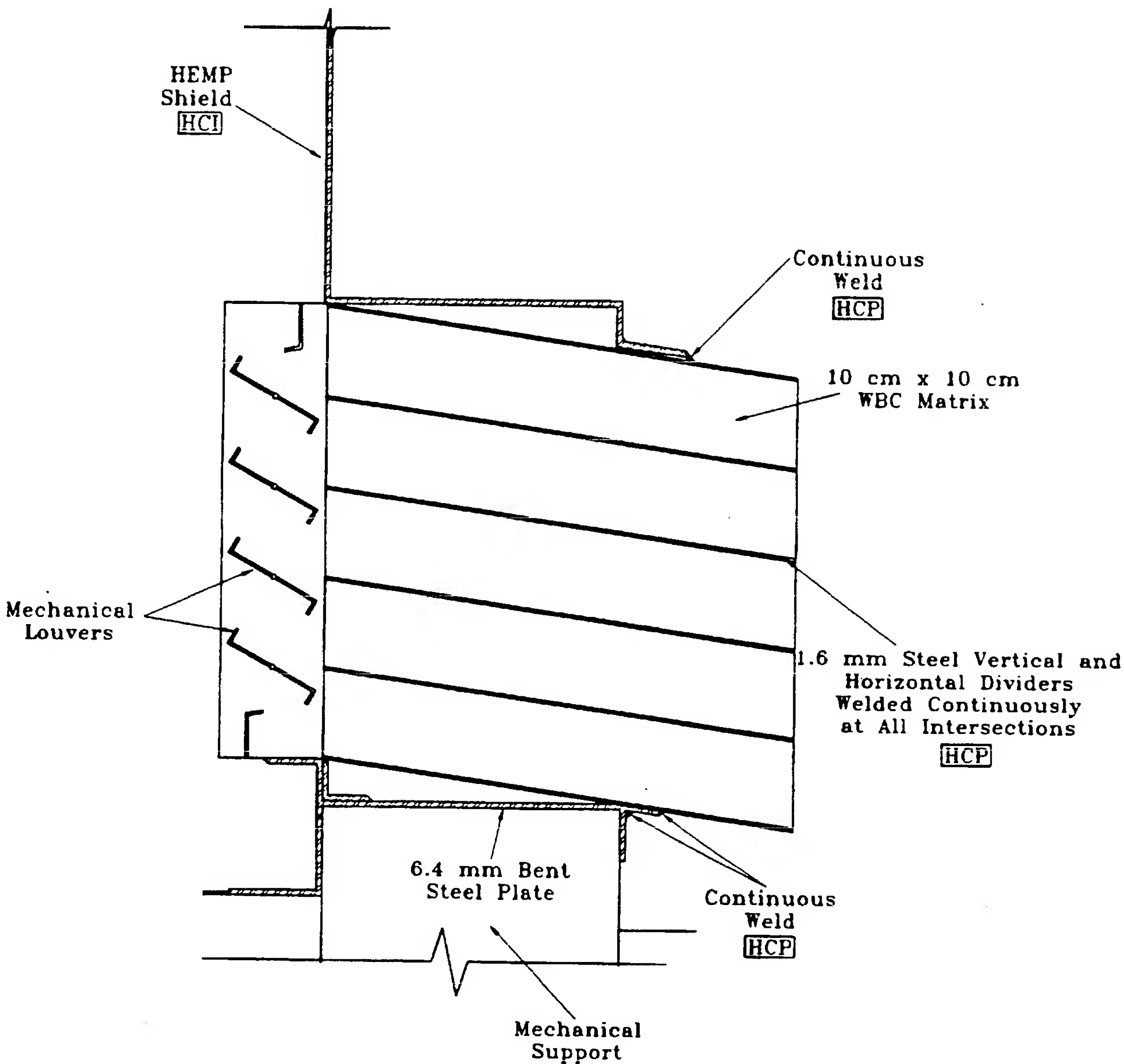


FIGURE 57. Alternate installation of a WBC array.

has a typical waveguide cell diameter in the range of 3.2 mm (0.12 in) to 6.4 mm (0.25 in) and is designed to provide shielding at frequencies extending to 10-40 GHz. Because of this small cell size, the thickness of a commercial honeycomb panel is of the order of 5 cm (2 in).

The disadvantages of commercial honeycomb, as compared to the shop-fabricated welded WBC matrix discussed earlier, are related to durability. Specific problems that have been experienced include the following:

a. The small cells tend to clog with dirt and must be cleaned frequently; the small cell size also produces a larger pressure drop at a given flow per unit area.

b. The commercial honeycomb is fragile and easily damaged by accidental contact.

c. The honeycomb and solder joints used to bond it electrically to the frame can be damaged by the heat from welding the panel to the shield; vibration can also cause the solder joints to fail.

d. The honeycomb is subject to galvanic corrosion where it mates with a dissimilar metal; it can also erode due to the moving fluid stream.

e. The honeycomb is difficult to repair; a complete section must normally be replaced when damaged.

For these reasons, commercial honeycomb panels are not recommended unless physical constraints limit the panel thickness or the barrier has shielding effectiveness requirements at frequencies above the range specified in MIL-STD-188-125.

When a commercial honeycomb WBC ventilation panel is required, it should be constructed as shown in figure 58. Overall dimensions of the array are determined from the required air flow and the allowable pressure drop. The manufacturer's technical data sheet will normally include a graph of pressure drop versus air flow per unit area. Honeycomb is generally manufactured in sections measuring about 0.5 m x 0.5 m (20 in x 20 in). Larger panels can be constructed with multiple sections that are either individually framed or carefully soldered at the seams. The honeycomb material is aluminum, steel, or brass with various platings; tinned brass is generally preferred.

The honeycomb material should be soldered to the steel frame, and the frame is then circumferentially welded into the HEMP shield. The panel must be specified to have a steel frame that is suitable for welding, with a flange of sufficient width to protect the honeycomb and soldered joints from the process heat.

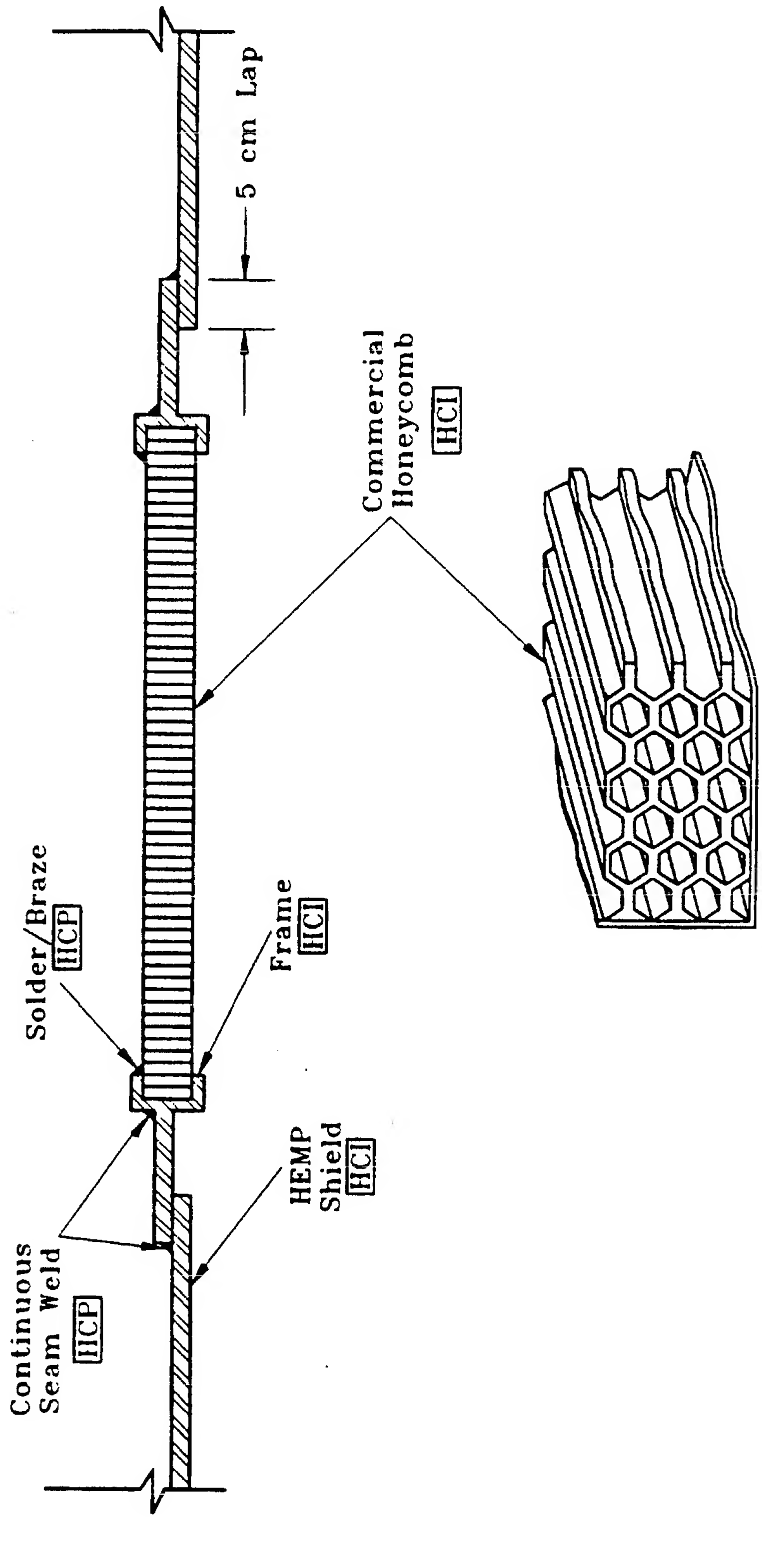


FIGURE 58. Commercial honeycomb ventilation WBC array panel.

Fans and louvers used with the honeycomb WBC ventilation panels should be placed inside the protected volume, so that the associated wiring and operating mechanisms are not required to penetrate the barrier. It may be desirable to protect the honeycomb from clogging and from water droplets or particles in the fluid stream by use of a replaceable air filter. Access for inspection and maintenance must be provided. A supply of clean, dry compressed air should be available for cleaning purposes.

10.3.4 Mechanical POE protection in copper shields. The principles of protecting piping and ventilation penetrations through copper shields are identical to those for steel shields. The materials and sequence of installation may differ.

The WBC devices must be constructed of a metal or must be metal plated for galvanic compatibility with copper. Handbook section 15 addresses the corrosion protection issues.

In a steel shield, the protection devices are usually installed in a nearly completed enclosure. Since the copper cannot provide support for pipes and ducts, however, the POE protection devices will normally be installed first. The copper sheets will then be installed and brazed to the devices.

10.4 References.

10-1. "Military Standard - High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

10-2. McInerney, M. K., S. Ray, R. McCormack, S. Castillo, and R. Mittra, 'The Effect of Fluids on Waveguides Below Cutoff Penetrations as Related to Electromagnetic Shielding Effectiveness," USA-CERL TR M-354, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, IL, July 1984.

11. STRUCTURAL POINTS-OF-ENTRY

11.1 Basic principles. Structural points-f-entry are the metallic structural elements of a HEMP-hardened facility that penetrate or become part of the electromagnetic barrier. Principal examples include load-bearing columns, walls, and beams. Penetrations by nonmetallic structural members are prohibited by MIL-STD-188-125 (reference 11-1), because effective shield closure cannot be achieved. As a design objective, the facility should be configured to minimize the number of structural POEs through the barrier.

Other potential structural POEs include devices for securing nonload-bearing walls, for anchoring the shield to the surrounding construction, for mounting items to the shield, and for similar applications. These requirements are also addressed in this section, and it is found that POEs can be avoided in the majority of these instances.

The need for structural POEs at a particular facility depends to a large extent on how the shield is designed and where the shield is located in relation to the building structure. For example, the HEMP shield can be a part of the structure, or it can be located within the structure. The shield may enclose almost the entire interior, or it may only provide protection for a room or a few rooms within the building. Each design must be evaluated to determine how best to address structural requirements. This evaluation must take place early in the design phase to be fully effective. The HEMP shield designer should work with the structural and the architectural design specialties to arrive at an optimum approach for the project. Factors to be considered include cost, ease of construction, space considerations, ease of incorporating other design specialties, and practicality.

Structural POEs, if required, are shown on the architectural and structural drawings. Whenever a metallic structural member must penetrate the barrier, the HEMP protection required by MIL-STD-188-125 is provided with continuously welded or brazed seams and joints between the penetrating element and the shield.

11.2 MIL-STD-188-125 requirements.

> 5.1.6.1 HEMP protection for structural POEs. HEMP protection for structural POEs, including beams, columns, and other metallic structural elements which must penetrate the electromagnetic barrier, shall be provided with continuously welded or brazed seams and joints between the penetrating element and the facility shield. As a design objective, the facility should be configured to minimize the number of metallic structural elements required to penetrate the barrier. Nonmetallic structural elements shall not penetrate the electromagnetic barrier.

11.3 Applications.

11.3.1 General guidance. The structural design of a particular HEMP-protected facility should be a joint effort of the architect, the structural engineer, and the shield designer. The design should be easy to construct, cost-effective, and reliable from a life-cycle standpoint. However, there is no one "correct" way to accomplish these objectives.

The following paragraphs describe an overall concept for a shielded building and the treatment of structural POEs associated with this concept. An understanding of the underlying principles found in these examples should allow the designers to handle other possible situations.

11.3.2 Shielded building concept. The overall concept for the structural design of a HEMP-shielded facility consists of an electromagnetic barrier within an outer building shell, as indicated in the plan view of figure 59. There is no preference based upon shielding considerations regarding the type of construction for the outer building. It may therefore be poured concrete walls, masonry, structural steel with metal siding, or any other type chosen for architectural compatibility and minimum construction costs.

The outer shell protects the shield from direct solar heating and exposure to temperature extremes. For the same reason, the building thermal insulation should be placed outside the electromagnetic barrier, so that both sides of the shield are in the environmentally controlled zone. A shield exposed to the sun and the weather is extremely difficult to construct and maintain. Therefore, an exterior shield must be eliminated from design consideration unless no other viable alternative exists.

Whenever possible, spacing between the exterior construction and the shield should be sufficient to permit access to the outer surface of the shield for inspection and repairs. This is accomplished in the design of figure 59 with a freestanding, steel-framed shield, typically separated from the outer shell by about 1 m (3.3 ft). A corridor of similar width should be reserved immediately inside the barrier to provide access to the inner shield surface. Easily removable, interior, wall-finish panels can be installed on the shield surfaces.

The advantages of this concept are improved maintainability and testability for the HEMP protection subsystem and design simplicity. The exterior structure and the shielded enclosure are relatively independent. Structural POEs for support of the shell should be limited to those required for roof support. The supporting structural members for the shielded enclosure may either be integrated into the shield configuration or attached to

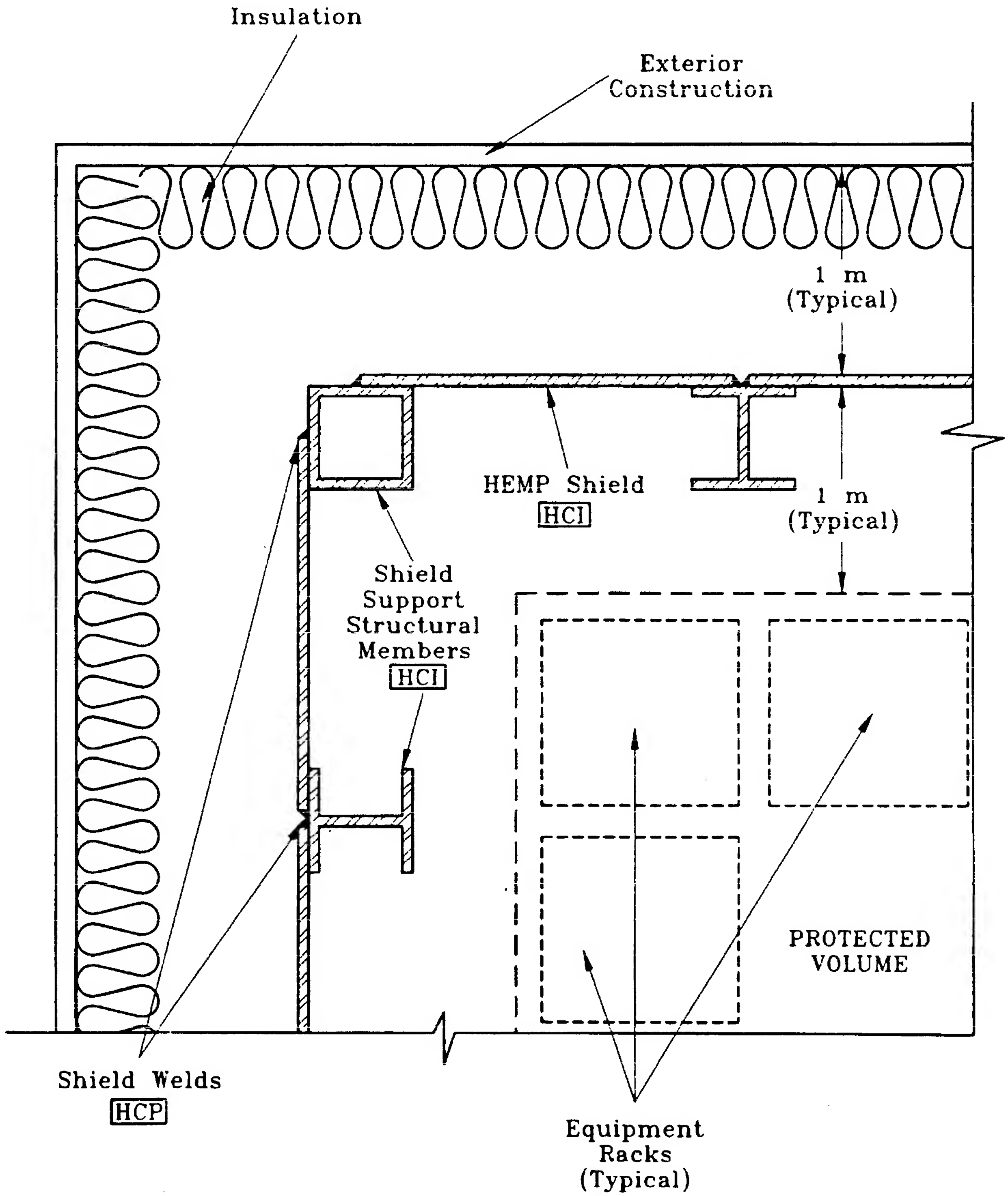


FIGURE 59. Overall shield concept.

it. The additional building floor area required to provide the inspection zones should be low-cost space.

11.3.3 Expansion joints. The HEMP shield must be designed to accommodate the same types of movement as any other structure, including displacements caused by settling, seismic activity and other transient ground motion, and thermal expansion. The design is complicated by the fact that the shield must retain its electromagnetic integrity, in addition to its ability to sustain movement.

The primary means for providing freedom of shield motion is a shield expansion joint. An expansion joint may be required in the shield, depending upon the anchoring details, where the barrier passes over a building joint. The building joint allows relative motion between different parts of the exterior structure, and the shield expansion joint should permit an equivalent amount of shield motion.

The triangular shield expansion joint design shown in figure 60 will expand or contract laterally by approximately 6 mm, and it will also allow several degrees of rotation about the joint axis. The amount of movement permitted is determined by the dimensions of the V-shaped notch and the thickness of the material. The expansion joint section is installed with continuous seam welds to the shield on both sides. The triangle may point either inward or outward, depending upon the particular application. Where there is personnel traffic, the joint should be covered to avoid a tripping hazard.

An alternate design for the expansion joint employs a half cylinder, rather than the triangular shape. The radius of the half cylinder and thickness of the metal determine the allowable displacement or rotation. This alternate design avoids concentration of stresses at a single point in the cross section.

Structures supported on separate foundations will experience differing displacements due to settling, seismic activity, or ground shock. Thus, a shielded passageway or duct between two buildings must also be provided with one or more expansion joints. The specific design and placement of the joint or joints will depend upon the expected amount of relative motion.

Expansion joints may have to be designed into the building shield to accommodate shield expansion and contraction due to temperature changes. The amount of unrestrained thermal expansion in any linear dimension of a material can be calculated as follows:

$$\delta = \alpha \, \Delta T \, L \tag{13}$$

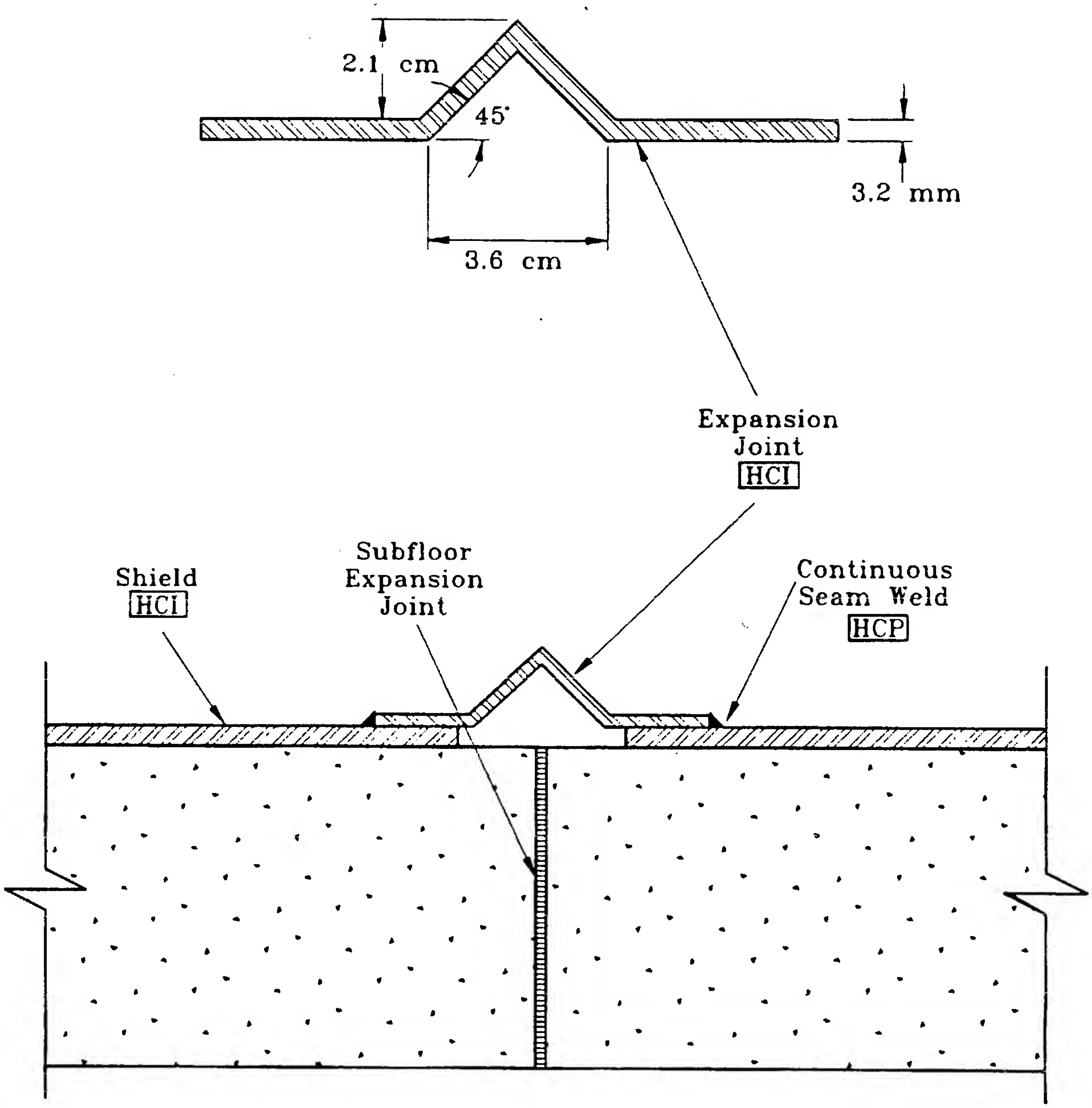


FIGURE 60. Shield expansion joint.

where

δ = total deformation due to thermal effects (meters)

α = thermal expansion coefficient of the material [meters/(meter-C°)]

ΔT = change in temperature (C°)

L = length (meters)

If the barrier is installed within the environmentally controlled zone of the building and is not normally subjected to significant temperature changes, the requirements for expansion joints are reduced. However, the designer must still ensure that the shield integrity will be maintained during temporary outages of the environmental control equipment.

11.3.4 Interior support columns. Figure 61 shows a possible shield configuration at an interior I-beam column that is anchored in a structural pier and supports the roof joists. The shield must be made continuous at the interface with the beam. This can be accomplished by fabricating a two-piece weld plate with special cutouts to fit closely around the structural member. The I-beam is peripherally welded to the plate as illustrated in the drawing, and the plate is circumferentially welded to the adjacent shield surface. This type of treatment can be used for a metallic support column, where there will be no significant movement of the pier relative to the subfloor slab and the floor shield.

A second HEMP shield design at an interior support column is illustrated in figure 62. This arrangement has no rigid attachments between the column and the shield and thus accommodates a relative motion of the two elements. Note that the boxlike, vertical shield framework wraps the barrier topology around the column and excludes it from the HEMP-protected volume. Since the column does not actually penetrate the shield, this configuration can be used with either a steel or concrete support member.

The boxlike shield can be constructed in the shop from steel angles and sheets in two or more pieces. The U-shaped assembly that is designed to fit around three sides of the column and a flat plate to form the fourth side can be fabricated separately, for example. They can then be installed and assembled at the construction site. Figure 63 shows one of many possible designs for joining the vertical and horizontal shield surfaces. Stiffeners for the column shield can be steel angles, as *seen* in the illustration, or square metal tubing. All of the welds shown in the drawing are continuous primary shield welds and are hardness critical processes.

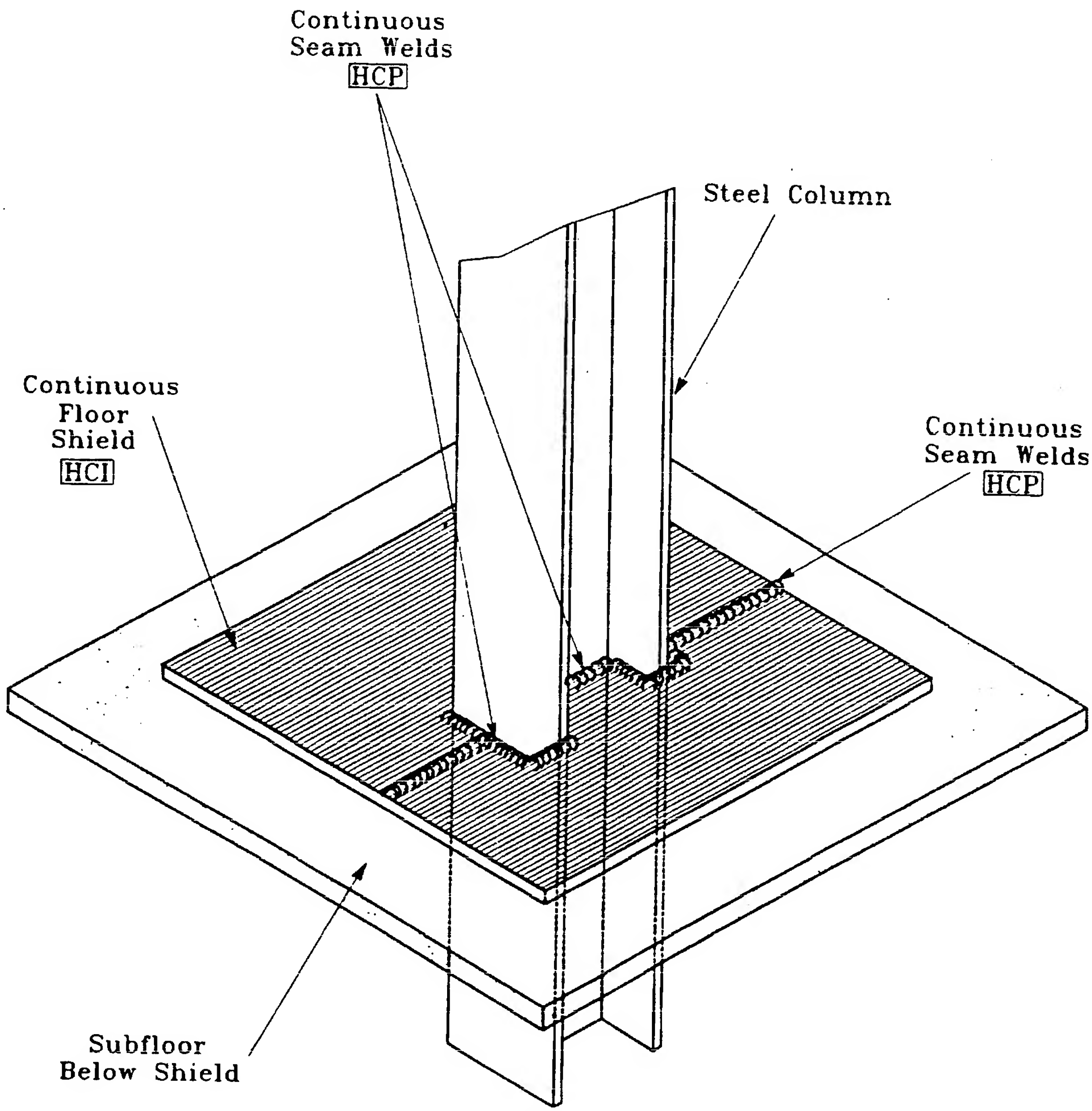


FIGURE 61. Shield configuration at an interior column with rigid attachments.

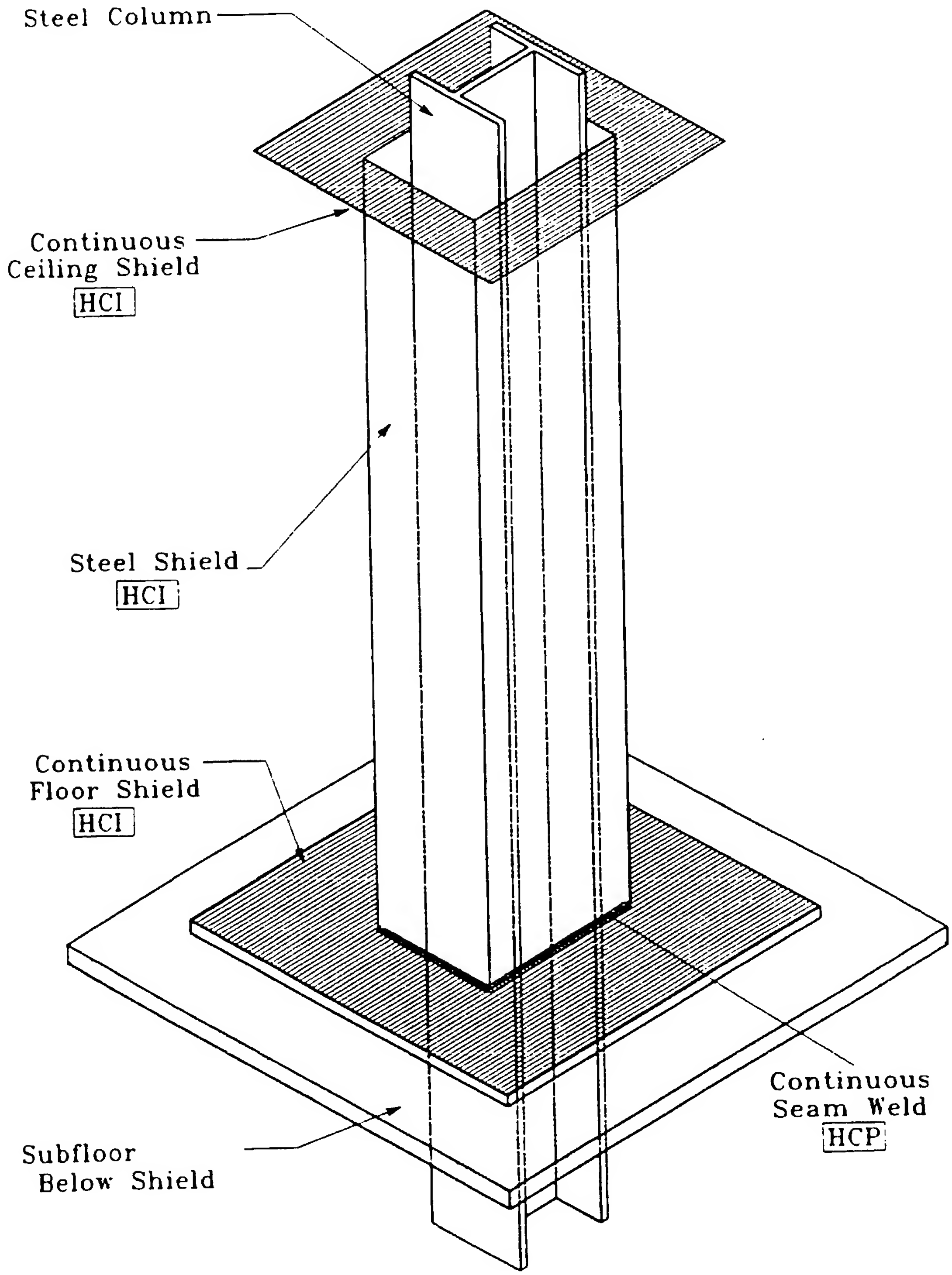


FIGURE 62. Shield configuration at an interior column with no rigid attachments.

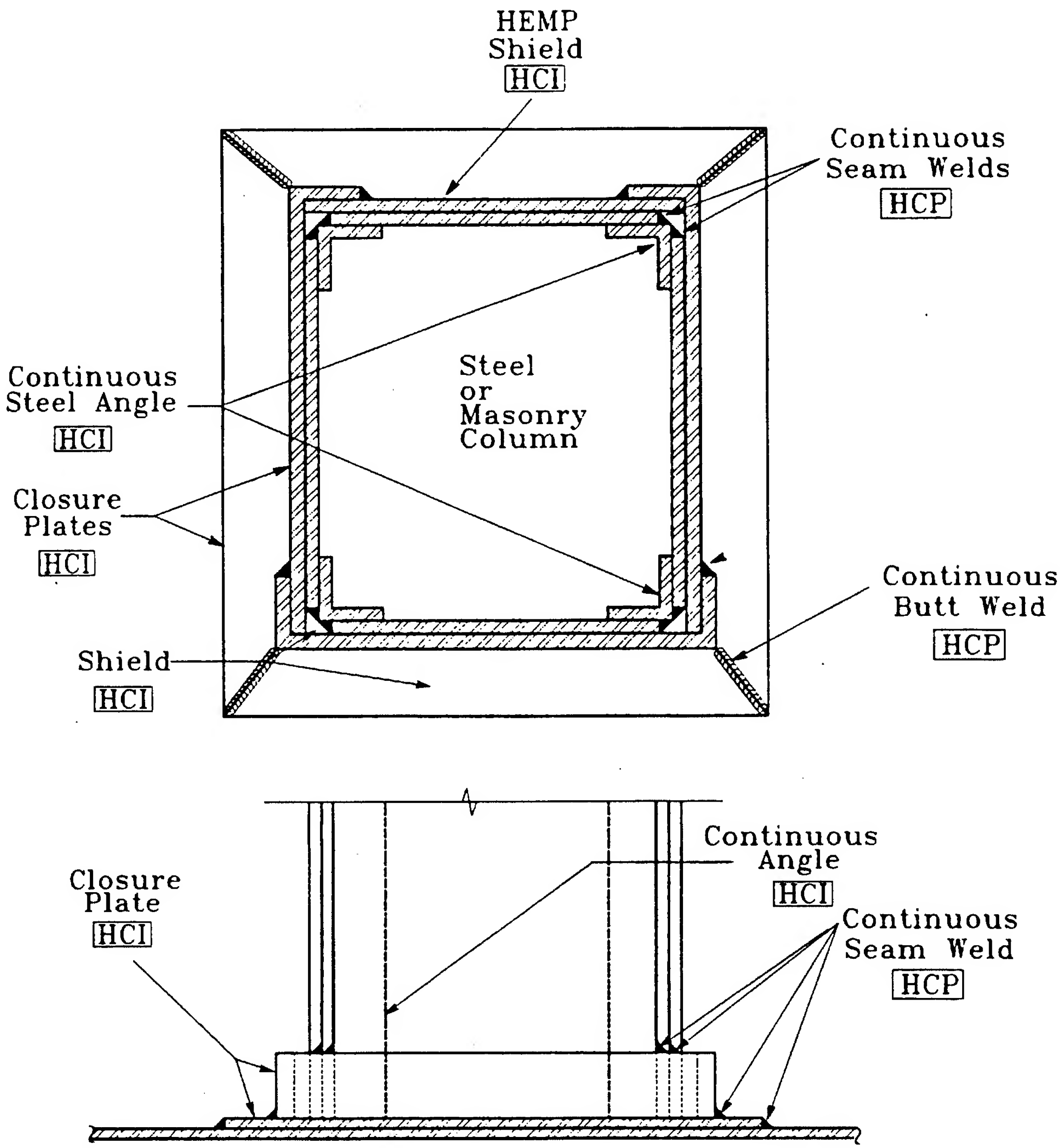


FIGURE 63. Plan and elevation drawings of a column shield assembly.

If it is necessary to connect the column shield to the column for structural support, the method of attachment must permit relative motion between the two elements. This can be accomplished with brackets that are flexible and with elongated/enlarged bolt holes.

An alternate steel column treatment that permits movement of the pier relative to the structural slab is shown in figure 64. This treatment is fundamentally the same design previously illustrated in figure 61, with modifications that permit the addition of an expansion joint. This expansion joint principally provides freedom of vertical motion, but slight relative lateral displacement or tilt can also be accommodated. Maximum requirements for movement should be predicted; additional flexibility should be designed into the configurate ion as needed. The box assembly must be welded on all seams, and the interfaces to the floor shield and column must be continuously welded. Welding is used here in a generic sense and is intended to include brazing. Any standard construction method for connecting the column to the pier (shown here as employing anchor bolts) can be used. Note, however that maintenance access to this connection can only be obtained with great difficulty.

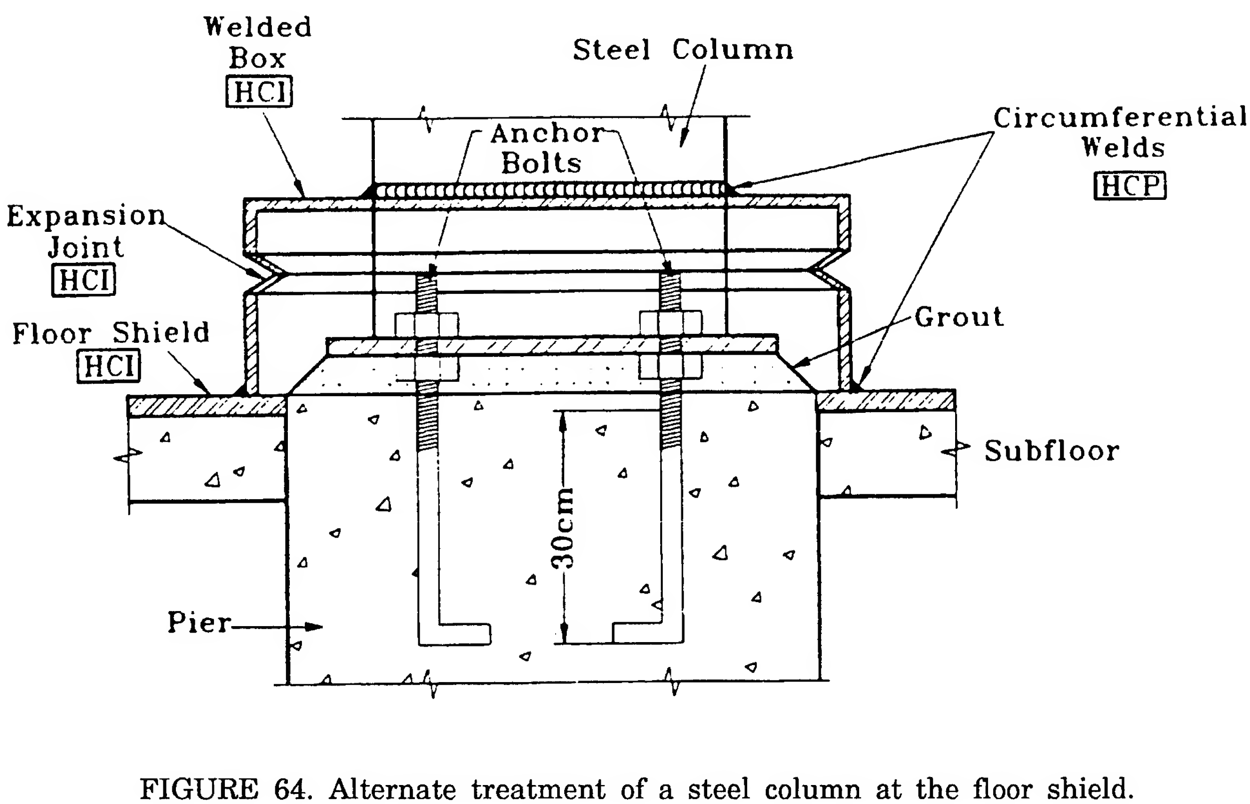


FIGURE 64. Alternate treatment of a steel column at the floor shield.

11.3.5 Interior walls. Interior walls may be structural (load-bearing), or they may serve only as partitions in a nonload-bearing capacity.

Shield design approaches at an interior structural or load-bearing wall exclude the wall from the HEMP-protected volume in a manner similar to that shown in figure 62 for an interior support column. Such designs result in large areas of the shield that cannot practically be accessed for maintenance and repair from both sides. Wherever possible, therefore, interior load-bearing walls should be avoided. If the building size and structural requirements dictate additional supporting members, interior columns should be provided in preference to a structural wall.

Figure 65 shows a typical installation for a partition wall in a shielded facility. A runner or stud track is placed on and attached to the floor shield as a base for the partition wall studs. A deep stud track is used at the ceiling to accommodate an appropriate amount of relative vertical displacement. The runners are fastened to the shield with tack welds, exercising care to ensure that there are no "burn-throughs" of the shield.

In an unshielded building, the runners are often attached to the underlying floor slab with explosively driven pins or anchors. This method must not be used in the design illustrated by figure 65, because the pins or anchors create shield POEs that are virtually impossible to electromagnetically seal. The method can be used in a HEMP-shielded facility when a wear slab has been poured on top of the floor shield, but only when precautions are taken to guarantee that the pins or anchors do not penetrate the barrier.

11.3.6 Beams. Various beams are employed in the design of a HEMP-protected facility to provide structural support for the outer building and the shield. The most common types of structural beams are constructed of either reinforced concrete or steel.

The structural design of the building should generally not require steel building support beams to penetrate the barrier. If such a structural steel POE is necessary, however, any of the protection techniques described for a column in 11.3.4 can be employed.

Concrete building support beams are not permitted by MIL-STD-188-125 to penetrate the electromagnetic barrier, because it is impossible to properly treat a nonmetallic structural POE. If a concrete beam is required to pass through the protected volume, therefore, the beam must be excluded from the volume with an approach similar to the column shield shown in figure 62.

In some past HEMP hardening projects, shield walls and ceilings have been anchored to concrete beams and surfaces of the outer building and have even been used as the form

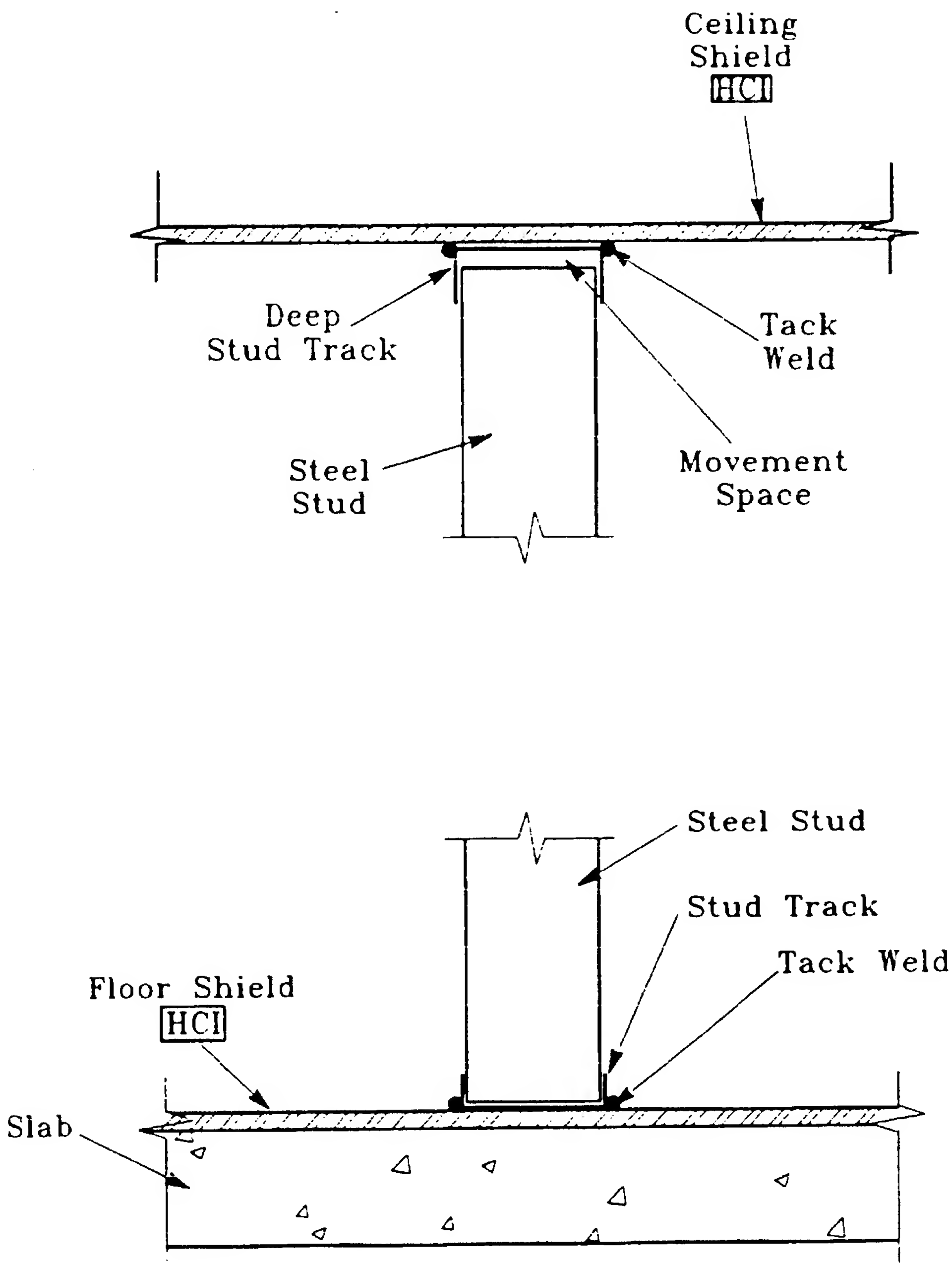


FIGURE 65. Partition wall installation.

for the concrete pour. While these practices are not prohibited by MIL-STD-188-125, they are discouraged because they restrict inspection and maintenance access to one side of the shield surface.

Steel beams will normally be used to support the shielded enclosure structure, and these beams can either be integrated into the shield design or simply attached to the shield. Figure 66 illustrates the case where the I-beam is continuously welded to the steel sheets and forms part of the shield. The shield is closed without incorporating the beam in figure 67, and the structural member is tack welded to the enclosure as needed for support.

11.3.7 Attachment to the floor slab. It is frequently necessary to anchor the HEMP floor shield into the structural subfloor for the purpose of controlling buckling. Illustrations of the use of furring strips and weld backing surfaces imbedded in the floor slab are presented in section 8. Figure 68 shows some additional methods of attachment, including techniques that employ explosively driven pins and anchor bolts.

The first two examples of figure 68 use the explosively driven pins, which are fired through the steel and into the concrete. Various types of pins, guns, and cartridges are

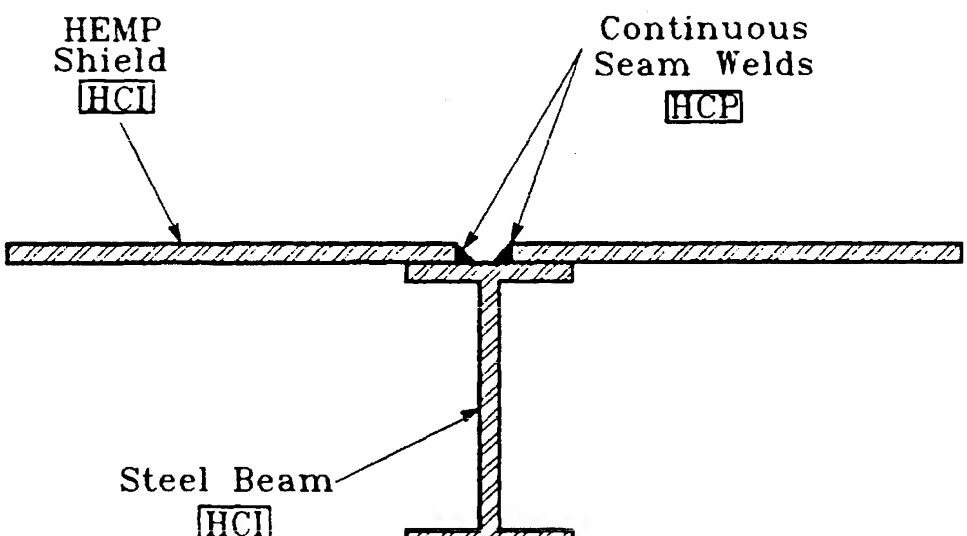


FIGURE 66. Steel beam incorporated into the HEMP barrier.

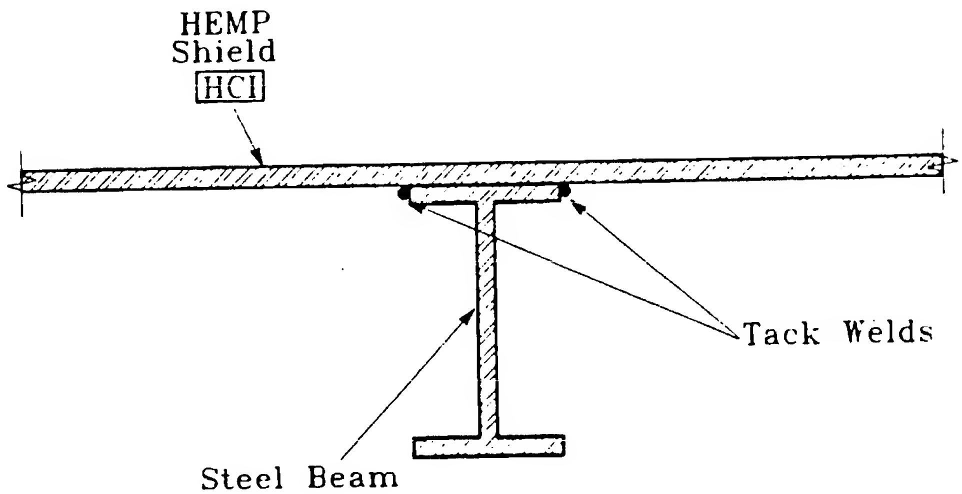


FIGURE 67. Steel beam not incorporated into the HEMP barrier.

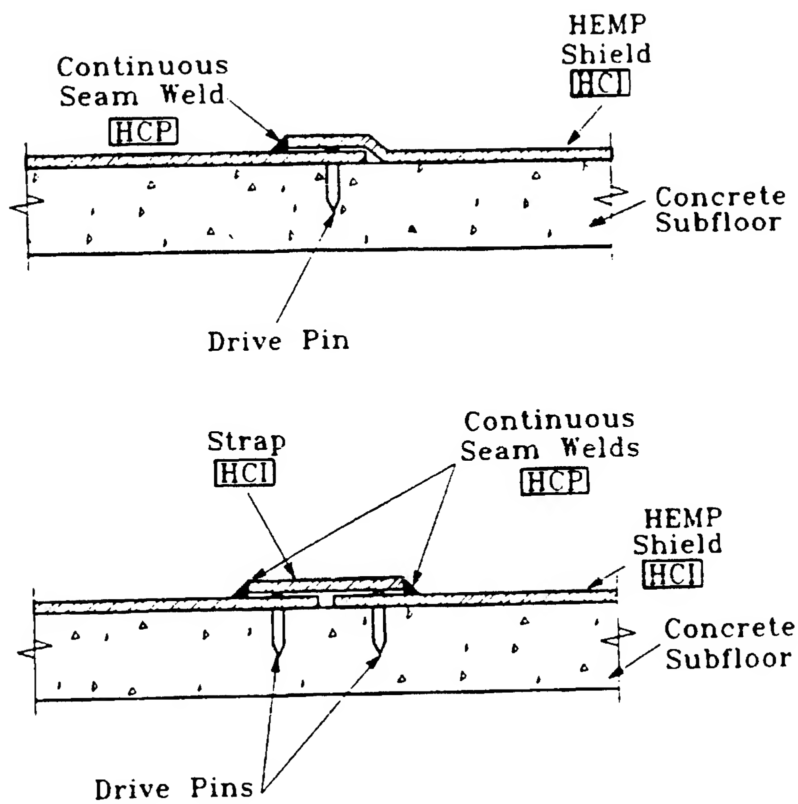


FIGURE 68. Floor shield attachment to the slab.

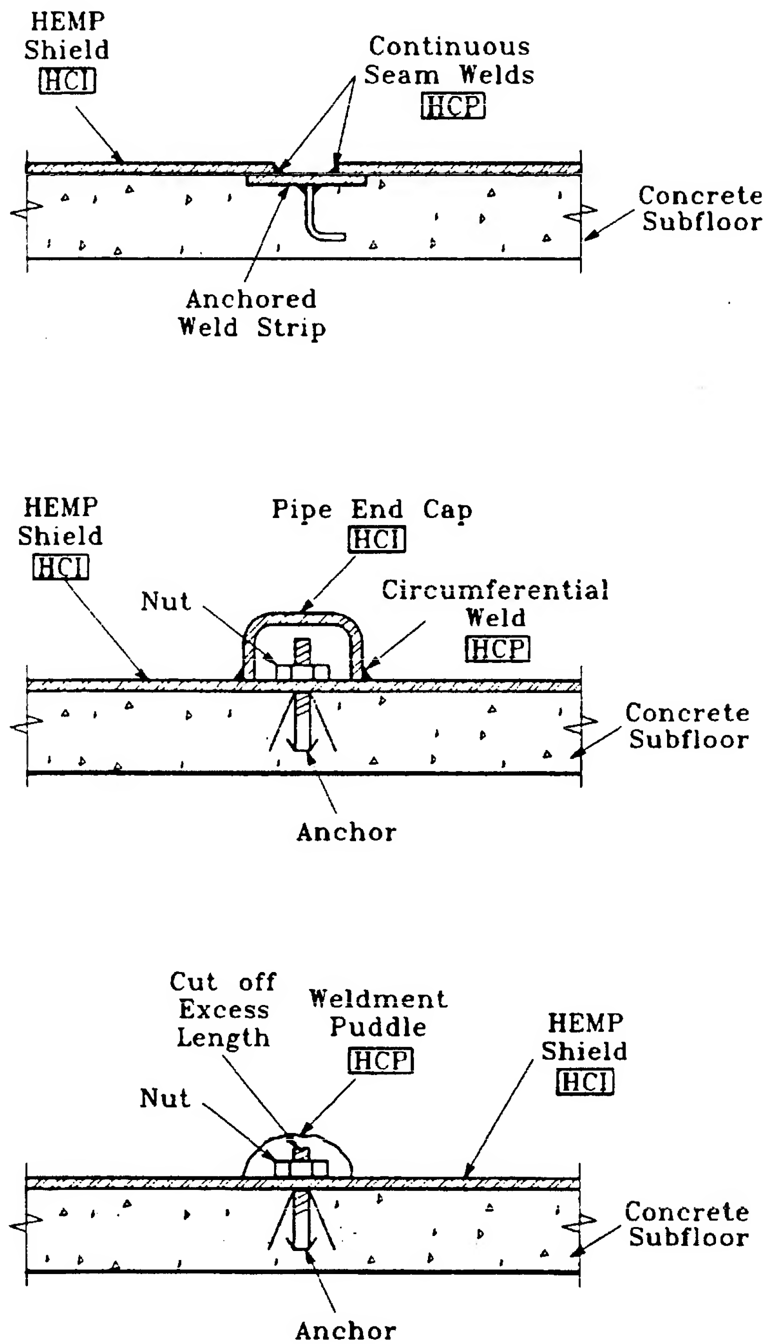


FIGURE 68. Floor shield attachment to the slab (continued).

commercially available. The pins will penetrate a thickness of steel up to 1.3 cm (0.5 in). Steel must be welded over the head of the pin, as indicated in the various drawings, to prevent the pin from becoming a POE.

The third illustration in figure 68 was discussed infection 8. In this case, the shield is anchored to the concrete subfloor with an imbedded metal strip that also functions as a backing material for the seam welds. Alternatively, plug welds can be used to attach the shield to an anchored furring strip (see figure 23, section 8).

The fourth and fifth examples employ the anchor bolt, which is installed in a predrilled hole through the steel and into the concrete. As the nut is tightened, the wedges expand outward and the steel is drawn toward the interface. Two different methods for sealing around the head are shown in these sketches.

It is not necessary to tie the shield to the floor slab except for the purpose of controlling buckling.

11.3.8 Attachments to the shield surface. In general, mounting of electrical panels and other items on the shield wall should be avoided. Where it is necessary to provide a shield wall mounting, the designer must ensure that the weight of the attached item will not place excessive mechanical stress on the shield.

Exceptions to this general rule include suspension of a false ceiling and overhead light fixtures from the shield ceiling. This must be accomplished in a way so that the shield ceiling is not excessively stressed and the barrier is not compromised. Two methods for attaching to the ceiling shield are shown in figure 69. The clip angle or universal channel (unistrut) is tack welded to the shield, making sure that the welding does not burn through the shield.

The thickness of the steel sheet used for the ceiling shield and the framing must be sufficient to support the total weight to be suspended. Heavier items should be placed only at locations where the shield is attached to the structural frame.

11.3.9 Copper shields. As discussed in section 8, a copper shield has virtually no strength or rigidity. All structural properties of the shielded enclosure must therefore be provided by the framework and the surfaces to which the copper sheets are attached.

The same principles of HEMP protection at structural POEs apply to both steel and copper shields. They must be implemented on a brazed copper enclosure in a manner that places no tensional, tearing, or puncture stresses on the copper sheets.

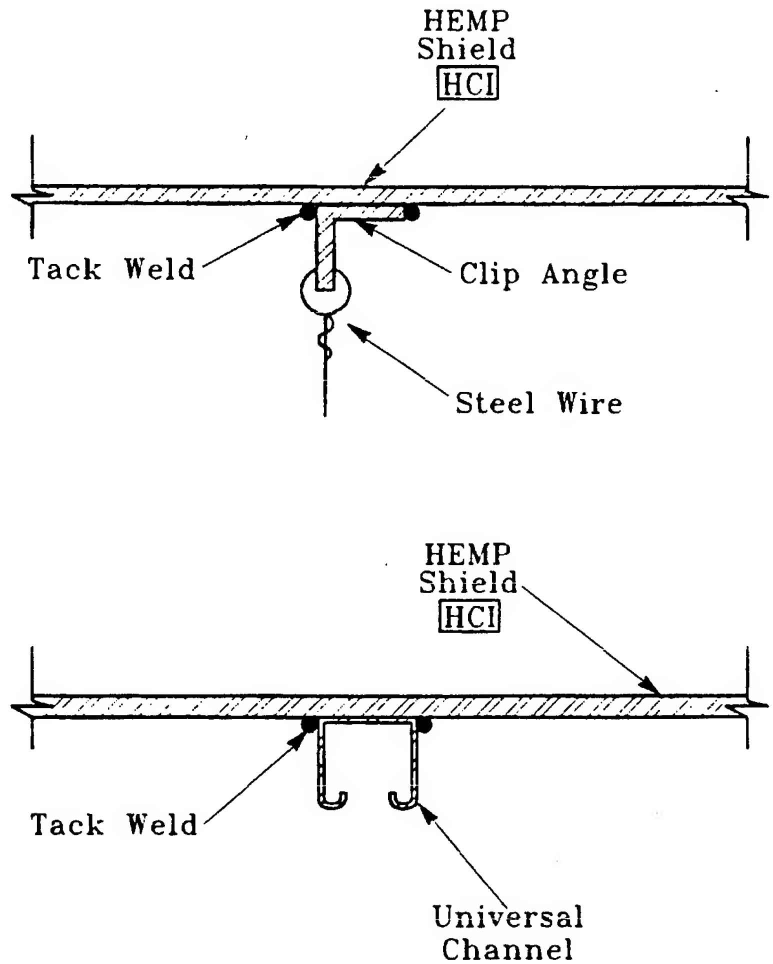


FIGURE 69. Typical techniques for attachments to the shield.

11.4 References.

11-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

12. ELECTRICAL POINTS-OF-ENTRY

12.1 Basic principles.

12.1.1 Introduction and overview. This section deals with the treatment of electrical points-of-entry to meet the transient suppression/attenuation requirements of MIL-STD-188-125 (reference 12–1). In this discussion of basic principles, properties of barrier components such as surge arresters, filters, transformed, and fiber optic systems are described. The four subsections devoted to this purpose are as follows:

a. 12.1.2 Electronic surge arresters

b. 12.1.3 Filters

c. 12.1.4 Power apparatus for isolation

d. 12.1.5 Optical isolation devices

Subsection 12.2 presents the MIL-STD-188-125 general requirements for HEMP hardening electrical POEs. These provisions in the protection standard are applicable to all five of the major classes of electrical points-of-entry: intersite power lines, intrasite power line POEs to external loads, intersite audio/data lines, intrasite control and signal lines, and rf antenna lines.

The use of components described in the subsection on basic principles for protection of these major groups of electrical POEs are then discussed in 12.3. Five subsections devoted to this purpose are as follows:

e. 12.3.1 Treatment of commercial power line POEs

f. 12.3.2 Treatment of intrasite facility power POEs on feeders to external loads

g. 12.3.3 Treatment of intersite telephone audio/data line POEs

h. 12.3.4 Treatment of control and signal line POEs

i. 12.3.5 Treatment of antenna line POEs

The antenna line treatments can also be applied to other video frequency line penetrations.

Two additional subjects addressed in the applications subsection are HEMP protection of electrical penetrations using conduit shielding (see 12.3.6) and penetration entry area design (see 12.3.7). References are provided at the end of the section.

MIL-STD-188-125 explicitly requires that the number of points-of-entry be minimized. This requirement was established to reduce the number of hardness critical items that must be tested, monitored, and maintained throughout the life of the facility and to minimize the associated costs. The first recommendation for dealing with an electrical point-of-entry is, therefore, to eliminate it if possible. The system should be designed to minimize the amount of mission-essential equipment outside the shield and to minimize the number of hardwire data and control lines required to support this equipment.

There are a few electrical points-of-entry that cannot be eliminated. Most fixed facilities must operate normally from external (commercial) power sources. Hence, a commercial power line penetration will usually be necessary. Most facilities must also receive and transmit signals via antennas or fiber optic lines. Therefore, the emphasis in this section will be on the treatment of the commercial power points-of-entry and on fiber optic and antenna points-of-entry.

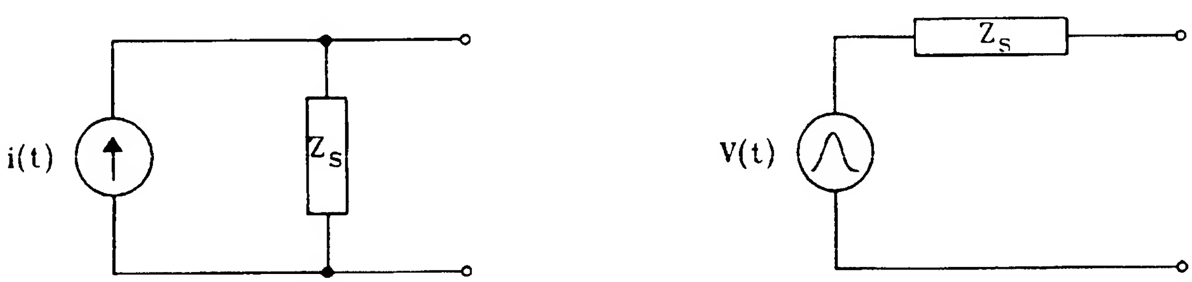
12.1.1.1 Stress on electrical POEs. The stress impressed on an electrical POE is the HEMP-induced current and voltage on the conductors outside the HEMP electromagnetic barrier. The largest response amplitudes and longest durations arise from HEMP interaction with long overhead lines, such as the commercial power transmission and distribution lines. The transient induced on an overhead line is the basis of the short, intermediate, and long pulses specified in MIL-STD-188-125. These are three double-exponential components of the HEMP-induced short-circuit current in overhead lines. All long conductors, whether buried or overhead, are subject to pulses such as these.

For purposes of predicting the response of a POE protective device, the exposed conductor and its HEMP-induced transient can be represented by a Norton-equivalent or Thevenin-equivalent source. Circuit parameters of the equivalent sources are summarized in table VIII. The equivalent circuits are illustrated in figure 70. The peak injected current specified in MIL-STD-188-125 is I_0 times the peak value of the difference of the exponentials. Risetime constant τ_r *is* 0.4 times the 10-90 percent risetime specified in the protection standard. The decay time constant τ is 1.44 times the full-width at half maximum amplitude (FWHM) of the prescribed pulse.

Table VIII also lists the equivalent source impedance Z_s for each of the three pulses. Although MIL-STD-188-125 does not specify the Norton-equivalent source impedances,

TABLE VIII. Parameters for the double exponential representation of the electrical POE sources.

Type of Pulse \ Pulse Parameter	Peak Current (Amperes)	Risetime Constant τ_r (seconds)	Decay Time Constant τ (seconds)	Source Impedance Z_s (ohms)
Short Pulse	8000	4×10^{-9}	7.2×10^{-7}	50-300
Intermediate Pulse	500	4×10^{-7}	7.2×10^{-3}	5-300
Long Pulse	200	2×10^{-1}	144	~5



$$i(t) = I_o \left(e^{-t/\tau} - e^{-t/\tau_r}\right)$$

(a) Norton Equivalent

$$V(t) = V_o \left(e^{-t/\tau} - e^{-t/\tau_r}\right)$$

(b) Thevenin Equivalent

$$V_o = I_o Z_s$$

FIGURE 70. Norton and Thevenin equivalent circuits for sources driving electrical POEs.

it is important to recognize that these impedances are finite and, in particular, that the source impedance for the long pulse is only about 5 Ω.

The short pulse represents the short-circuit transient current induced on overhead lines by the early-time HEMP. The source impedance of the Norton-equivalent source for the short pulse is a few hundred ohms for overhead feeders and a few tens of ohms for underground feeders or feeders in metal conduits. Thus, the voltages developed by the short pulse can be greater than 100 kV and are easily large enough to activate spark gap or metal oxide varistor surge arresters on ac power lines. The charge transfer (current impulse) for the 8 kA short pulse is 5.8 millicoulombs, and the rate of energy deposition is 23 joules per ohm.

The intermediate pulse is the short-circuit current response of the overhead lines to the intermediate HEMP wave. The Norton-equivalent source impedance for this component is about the same as that for the short pulse for times less than about 100 μs. For later times, the impedance is in a state of transition that ends in the quasi-static impedance of the distribution lines and their terminal ground impedances (see long pulse below). The open-circuit voltage developed by the 500 A intermediate pulse can, therefore, be 25 kV or greater. The charge transfer and action are 3.6 C and 900 J /Ω, respectively.

The long pulse represents the short-circuit current induced in a long line and its terminal resistance by the late-time MHD EMP. The Norton-equivalent source impedance is about 5 Ω. This is nominally the total resistance of the wires and ground electrode impedance for the distribution line serving the facility. The open-circuit voltage developed by this pulse source is only about 1 kV. The charge transfer and action of the 200 A long pulse are 29 kC and 2.9 MJ / Ω, respectively. The charge transfer is about 100 times that of a severe lightning flash, and the action would deliver 290 kJ to a 0.1 Ω load. The action and charge transfer are summarized in table IX, for comparison with these parameters for a severe lightning flash (reference 12–2).

12.1.1.2 Protection strategy. The strategy for dealing with electrical points-of-entry is to eliminate them where possible, to substitute mechanical or optical apparatus for electrical wires where practical, and to use surge arresters, filters, and isolators on the wire penetrations that cannot be eliminated or replaced with substitutes. It should also be noted that external circuits and their points-of-entry can be minimized by eliminating the need for a circuit, by extending the shield to enclose it, or by moving the circuit inside the HEMP barrier.

This section concentrates on the treatment of wire penetrations with nonlinear devices, filters, and power apparatus. However, the discussion of power apparatus (subsec-

TABLE IX. Action and charge transfer of the HEMP-induced pulses and a lightning flash.

Transient Type \ Characteristic	Action (joules/ohm)	Charge Transfer (coulombs)
HEMP Short Pulse	23	5.8×10^{-3}
HEMP Intermediate Pulse	900	3.6
HEMP Long Pulse	2.9×10^{6}	2.9×10^{4}
Typical Lightning Strike	1×10^{4}	30
Severe Lightning Strike	1×10^{6}	300

tion 12.1.4) also suggests using a motor-driven generator to deliver the power through shaft torque, rather than an electrical point-of-entry. Likewise, fiber optic isolators are recommended for most telephone, control, and signal lines.

Points-of-entry for local circuits that are not stressed by the intermediate and long pulse can be protected by fairly well established surge arrester and filter techniques (reference 12–3). The impressed HEMP stress on an intrasite line is the short pulse, and the surge arrester and filter are effective in diverting this transient to the outside of the shield.

For long electrical power and signal conductors that are subject to the intermediate and long pulse, a different strategy is required. These late-time effects are not easily diverted because the low-pass filters are transparent to them, and the charge transfer and action of the long pulse are beyond the capability of available surge arresters. For these reasons, interruption of the late-time current in the intermediate and long pulse is preferred. This strategy and its implementation for the treatment of commercial power feeders are described in 12.3.1.

Additionally, the primary shield is transparent at the frequencies contained in the long pulse currents.[3] In the tests conducted to date, long pulse excitation on the shields of ground-based facilities has not disrupted the operation of site equipment. Nevertheless, it is

[3] The diffusion time constant for 0.65-cm (0.25-in) thick mild steel ($\mu_r = 100$) is 30 ms, but the long pulse lasts over 100 s.

good practice to avoid deposition of long pulse currents on the shield where practical. This can be accomplished with fiber optic isolation in intersite audio/data lines and dielectric sections in long metal piping systems that connect to the shield.

The use of optical fiber links to interrupt the current on signal cables has already been noted. The optoelectronic converters for mission-essential systems must be provided with an uninterruptible power supply or supplied with protected power from the facility. In either case, care should be taken to avoid injecting the long pulse currents onto the HEMP shield where practical. This problem is discussed in 12.3.3.

Antenna lines, which are typically coaxial cables, are exposed to the HEMP fields at the antenna. The voltages developed in the antenna coaxial cables are sufficient to produce arcing in connectors and at the antenna terminals. Low-capacitance surge protection is recommended in 12.3.5 to prevent arcing. Additional filtering and surge limiting is recommended to reduce the HEMP stress to a level that the radio equipment can tolerate. It is recognized that surge limiting on transmitting antenna cables may not be sufficient to meet the 1 A residual current allowed by MIL-STD-188-125, particularly at high frequency (HF) and below. In such cases, a special protective volume must be developed for the radio in accordance with MIL-STD-188-125.

It is recommended in 12.3.7 that all external conductors, pipes, waveguides, and coaxial cables enter the shield at a single penetration entry area. Having a single penetration area restricts the flow of HEMP currents over the shield, where they may excite doors, ventilation POEs, and other imperfections in the shield.

12.1.1.3 Time-domain circuit analysis. To design and evaluate the transient suppression/attenuation protection on electrical POEs, it is strongly recommended that time-domain circuit analysis techniques (reference 12–3) be applied. The analysis of protection circuits containing filter and nonlinear surge arresters is facilitated by the use of one of the time-domain circuit analysis codes available for personal computers. With such codes, the residual transients inside the barrier can be calculated, and the performance of the protection for various input pulse amplitudes and waveforms can be assessed. To use these analytical tools, models of the surge arresters, filters, and transformers must be available. Specific circuit examples are provided throughout this section. However, commercial filters vary, and many manufacturers consider their filter designs to be proprietary. Some suppliers will provide sufficient information to perform the response analysis of the type demonstrated in 12.1.3 on a confidential basis. The preferred alternative is to measure the device terminal characteristics and impulse and step responses and use these measured results in the analysis.

12.1.2 Electronic surge arresters.

12.1.2.1 Basic principles. There are two categories of electronic surge arresters: those that impede surges and restrict their propagation toward sensitive circuits, and those that divert surges and limit voltages to unacceptable residual level. For surges that originate from a high-impedance source, complete blockage of a surge is seldom possible; thus, diverting the surge is more likely to find general application.

A combination of diverting and impeding can also be a very effective approach. This approach, illustrated in figure 71, also generally takes the form of a multistage circuit. The first device diverts the surge toward ground. The second device—an impedance or resistance--offers a restricted path to the propagation of the surge beyond the first diversion, but an acceptable path to signal or power transmission. The third device clamps the residual transient. This multistage concept is inherent to linear filters, consisting of shunt capacitors and series inductors, in which the frequency response of the combined elements is complicated as discussed in section 12.1.3.

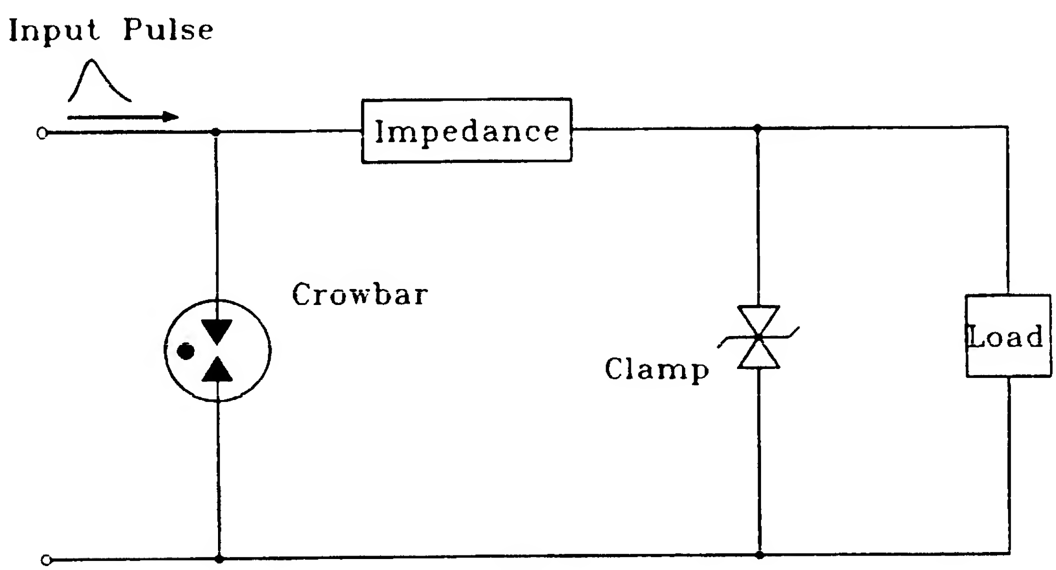


FIGURE 71. Basic multistage configuration of an ESA.

Surge-diverting devices can be of two kinds: short-circuiting devices ("crowbars") or voltage-clamping devices ("clamps"). Both involve nonlinearity, that is, the resistance of the device depends on the current flowing in or the voltage across the device. Depending on the type of device, this nonlinearity is the result of two different mechanisms: a continuous increase in the device conductivity as the current increases (clamps), or an abrupt switching as the voltage increases (crowbars). Standard symbols for these devices are shown in figure 72.

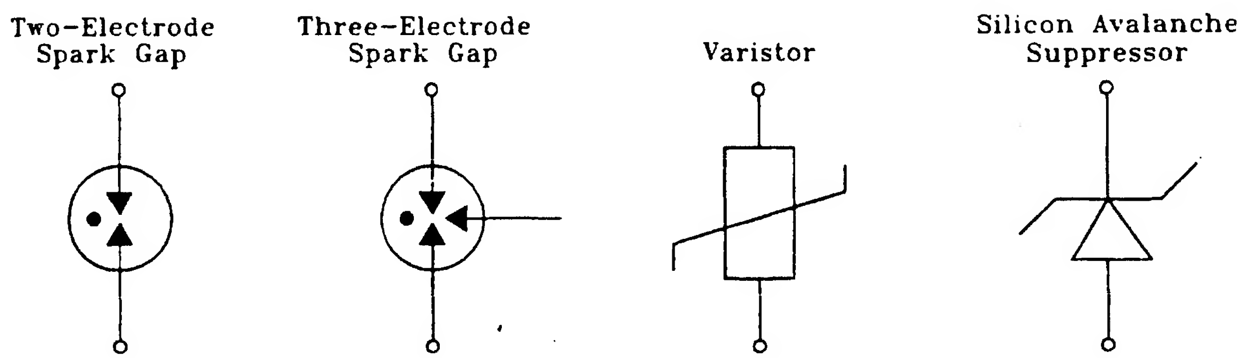


FIGURE 72. Transient suppressor symbols.

We will first examine the basic principles of single-component ESAs. Then the principles of applying these devices to protect electrical points-of-entry, as single-component or multiple-component packaged ESAs, will be discussed. Specific ESA designs will be described. Some comparisons will be made to point out the significant differences in performance; clarifications of some issues will also be given.

12.1.2.1.1 Principles of crowbar devices. The principle of crowbar devices is simple. Upon occurrence of an overvoltage, the device changes abruptly from its normal high-impedance state to a low-impedance state, offering a low-impedance path to divert the surge to ground. This switching can be inherent to the device: gas breakdown of a spark gap between two or more electrodes, or turn-on of a two-terminal multifunction semiconductor. Externally triggered devices are sometimes used, where a control circuit senses the rising voltage and turns on a power-rated semiconductor or thyristor to divert the surge.

The major technical advantage of the crowbar device is that its low impedance allows substantial surge currents without dissipation of high energy within the device itself. The energy has to be spent (charge transfer) elsewhere in the circuit. In the off state, many crowbars such as spark gaps have a very small capacitance across their terminals. This is an advantage over other ESA devices in high-frequency signal applications.

12.1.2.1.2 Principles of voltage-clamping devices. Voltage-clamping devices (clamps) exhibit a variable impedance, depending on the current density through the device. The impedance variation is monotonic without discontinuities, in contrast to the crowbar device, which exhibits a discontinuity by turn-on action. Unlike a spark gap or thyristor, the clamp may operate with no significant time delay.

Assuming the clamp capacitance is small, an installed clamp should only minimally affect the circuit before and after the transient for any voltage below clamping level. Increased current drawn through the device as a surge voltage attempts to rise results in voltage-clamping action. Nonlinear impedance means that this current increases at a higher rate than the voltage. The increased voltage drop across the source impedance caused by the higher current results in the apparent clamping of the voltage.

12.1.2.2 Device characteristics.

12.1.2.2.1 Technology of crowbars. Crowbar action can be obtained by two different phenomena, with essentially the same effect on the circuit. The first, based on breakdown of a gas between electrodes, has a long history of successful application. The second, based on junction semiconductor physics, has emerged as an alternative to the gas breakdown. The simplest gas breakdown mechanism can occur in air between two electrodes. Examples of these are the "arcing horns" in power equipment and the "carbon blocks" used in telephone equipment. A more controlled environment can be achieved by enclosing the electrodes in a sealed housing, so that a gas other than air at pressures other than atmospheric can provide design alternatives. These devices are known generically as 'gas tubes." The semiconductor junction devices are essentially based on the trigger action first developed for the thyristor device [also known as a silicon-controlled rectifier (SCR)].

12.1.2 .2.1.1 Gas tube technology. Gas tubes consist of two electrodes separated by a gap and contained in a sealed housing, filled with inert gas at a relatively low pressure. Figure 73 shows a simple configuration for a two-electrode gas tube. More than two electrodes can be contained in the same housing, for the purpose of obtaining simultaneous action for more than one pair of conductors. The operation of the device is based on cathode emission, leading to avalanche breakdown of the gas between the two electrodes.

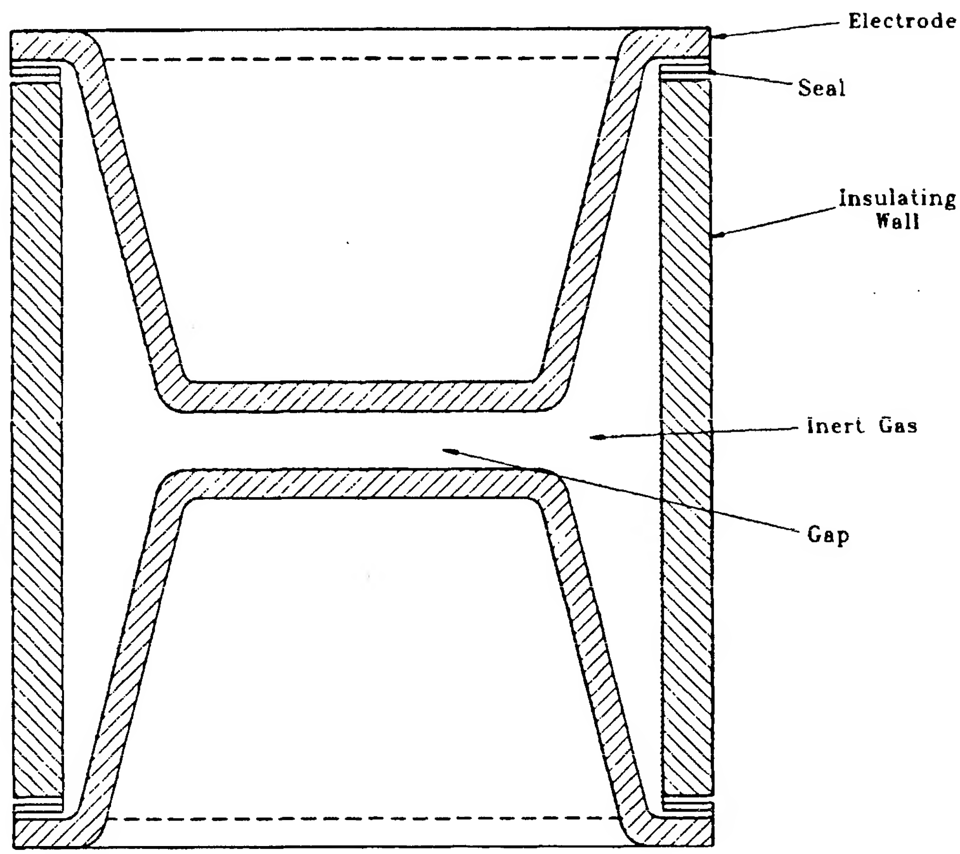


FIGURE 73. Simple configuration for a two-electrode gas tube.

For fast action, this breakdown is controlled by design factors that include the separation, shape, and surface coating of the electrodes as well as the nature and pressure of the gas.

A finite time is involved between the application of a surge voltage and full conduction by breakdown. In the first phase, a charged particle must appear in the gap to initiate ionization by electron multiplication. In the second phase, the ionization proceeds by avalanche to produce the low-impedance discharge path (references 12-4 and 12-5). Small quantities of radioactive elements may be introduced in the gas tube to stabilize the statistical time lag of the first phase, in effect reducing the voltage level of the breakdown.

In the nonconducting state, the impedance of the gas tube is principally the reactance of its inter-electrode capacitance. After full breakdown, a nearly constant, low voltage is maintained between the electrodes, in the range of less than 40 V. There is a transition region between a glow region and arc region (figure 74) in the volt-ampere characteristic of the device. The transition is influenced by the external circuit. In the case of the ESAs of interest here, there will be enough energy (current) available from the external circuit to produce a fast transition to the arc mode and its low voltage, rather than lingering in the glow mode and its intermediate voltage.

12.1.2.2.1.2 Semiconductor device technology. A thyristor can be triggered into conduction by a circuit that senses the rising voltage of a surge and applies a pulse to the gate, thus acting as a crowbar. By combining the function of the thyristor and the trigger circuit into a single multifunction device, greater speed of triggering can be obtained, into the nanosecond range. However, because the device involves very thin junctions, the capacitance of the semiconductor crowbar can be much larger than that of a gas tube of similar current handling capability.

12.1.2.2.2 Technology of clamps. The two major types of clamps are based on different technologies, but produce the same effect. Thus, the basic principles of application are the same, although some of the advantages and limitations may influence the choice in technology. The two categories of devices that have found acceptance in the industry are single junction silicon diodes and polycrystalline varistors. Two earlier and successful technologies, silicon-carbide varistors and selenium rectifiers, have been practically eliminated from the field because of the smaller size and superior characteristics of modern silicon diodes and metal oxide varistors. Both have a relatively high shunt capacitance.

12.1.2.2.2.1 Silicon diode technology. Zener avalanche diodes were initially applied as voltage clamps, a natural outgrowth of their application as voltage regulators. Improved construction, specifically aimed at surge diversion, has made these diodes very effective clamps, and they should not be confused with the voltage-regulating Zener diodes. Large-diameter junctions and low thermal impedance connections are used to deal with the inherent problem of dissipating the heat generated by the surge in the small volume of a very thin single-layer junction. In some applications, a stack of power-rated silicon diodes, used in the forward direction, provides a clamping action associated with the forward conduction drop.

12.1.2.2.2.2 Metal oxide varistor technology. The term varistor derives from the device's function as a variable resistor. Metal oxide varistors depend on the conduction process occurring at the boundaries between grains of oxide (typically zinc oxide) grown

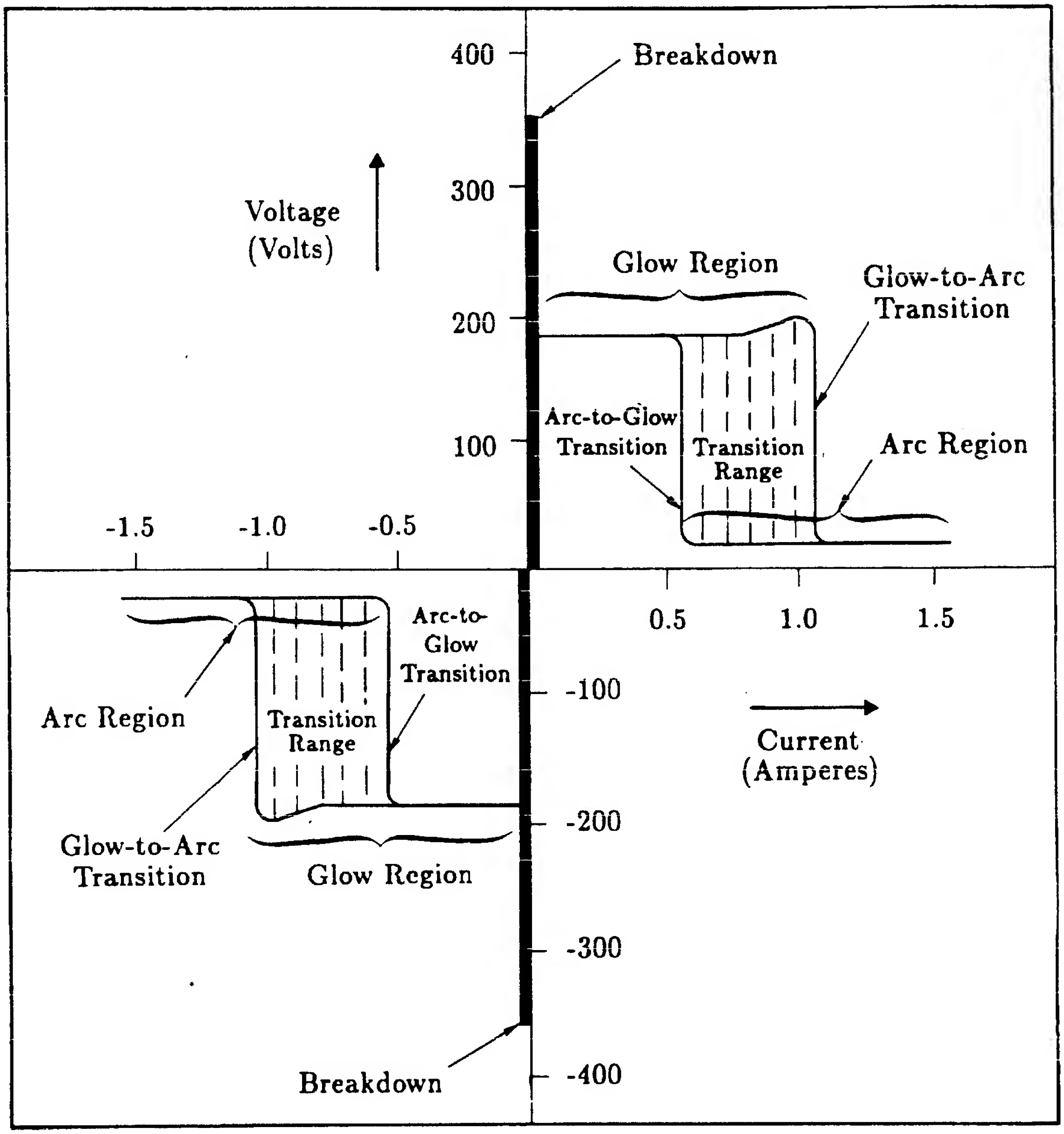


FIGURE 74. Volt-ampere characteristics of a gas tube.

in a carefully controlled sintering process. They have a relatively high shunt capacitance, a disadvantage in high-frequency applications. The physics of the nonlinear conduction mechanism can be found in the manufacturers' application notes.

12.1.2.2.3 Device applications. For successful application, the ESA must protect the system from the expected conducted transient, survive the input transient in the short term, recover standby conditions after the transient, have sufficient endurance to withstand usual transients, and not interfere with the normal operation of the system. Each of these requirements can serve as a criterion for evaluating a candidate ESA. Another significant factor may be cost, but it is not addressed in this document. Regardless of the quality of the ESA, its intrinsic performance must not be degraded by incorrect installation practices. To ensure that the expected performance is realized, the following basic installation guidelines should be followed:

a. Control of lead inductance is critical to the proper operation of ESAs, and shunt connection leads should be kept as short as possible. The length of wire connecting the ESA has an important effect on the effective speed of response of the device. The voltage across the stray inductance of the leads during the initial current rise is added to the expected, limited voltage across the terminals of the ESA. One centimeter (0.4 in) of lead wire adds about 10 nH of inductance to the ESA impedance.

b. Some ESAs, especially the crowbar type, can enhance the high-frequency components of a surge because of their fast turn-on action. Therefore, ESAs should be placed on the HEMP source side of a filter. In this combination, the ESA provides overvoltage protection for the filter components, while the filter provides attenuation of the high-frequency remnants (both the initial rise before the gap fires and the collapse of voltage upon firing of the gap).

c. It also is important in any installation to provide physical accessibility as well as electrical accessibility (including some form of temporary isolation if necessary) to allow testing for maintenance and surveillance.

12.1.2.2.3.1 Crowbar applications. The principal characteristic of the crowbar is its switching action from high to low impedance, with the resulting low voltage maintained across the electrodes by the continuing arc of the gas tube or the holdover of the junction semiconductor. Depending upon the characteristics of the external circuit, interrupting this continuing current may occur naturally or may require forced commutation. The resulting power loss or signal loss between the time of breakdown and the time of recovery may be undesirable, but it is an inherent and inescapable characteristic of all crowbars.

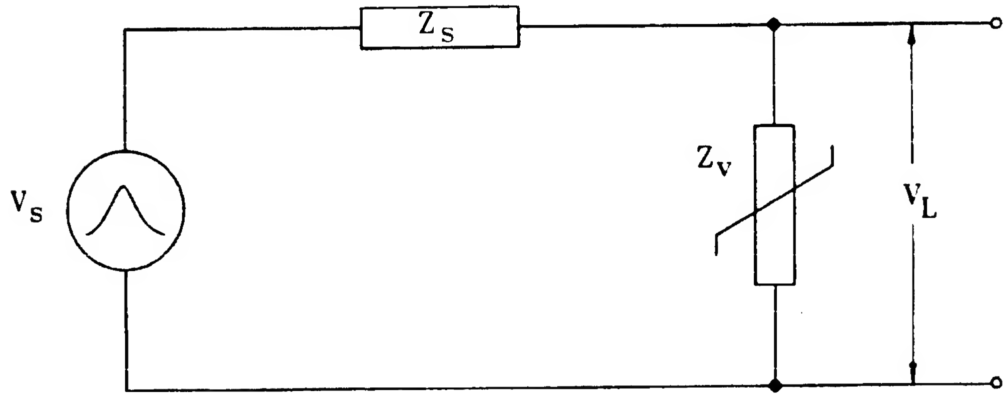
In low-power signal circuits, there is generally little energy available after the surge for maintaining a current flow through the device, so that recovery occurs naturally. Furthermore, a gas tube has very little capacitance between its electrodes. These two conditions make the gas tube a favored device for signal applications. In power applications, however, there is generally enough energy available after the surge to maintain current flow through the device. Some external means must therefore be provided to limit or even interrupt this current before the gap can recover its high-impedance characteristic.

12.1.2.2.3.2 Clamp applications. The clamping action of these devices depends on the combination of a finite source impedance and the variable impedance of the clamping device. Voltage and current divider principles are at work where the ratio of the divider is not constant, but changing. If the source impedance is very low, the voltage ratio would be near unity. In the limit, with a zero source impedance, the clamp could not limit the voltage (figure 75). However, the current will always be divided between the load impedance and the clamp impedance. For HEMP protection applications, the prime function of a clamp is to divert the current to the shield.

In the following description, a varistor is used, but the concepts are also applicable to silicon diode clamps. The characteristic of a varistor can be understood by examination of the equivalent circuit of figure 76. The major element is the varistor R_v, whose volt-ampere (V-I) characteristic is assumed to be defined by the expression $I = kV^a$, where k and a are device-dependent constants. A capacitor C and a leakage resistance R_p are in parallel with the varistor. In series with this three-component group, there is the bulk resistance of the zinc oxide grains, R_s, and the inductance of the leads, L.

At low current, only the varistor element and the parallel leakage resistance are significant. Under pulse conditions at high current, all but the leakage resistance are significant. The varistor provides a low impedance to the passage of the high current. At the upper limit of the conducting range, however, the series resistance will produce an upturn in the V-I characteristic-or an increase in the voltage across the device. The lead inductance can give rise to spurious overshoot problems if not dealt with properly. Depending on the application, the capacitance can offer either a welcome additional path for fast transients or an objectionable loading for systems operating at high frequencies.

When the V-I characteristic is plotted on a log-log graph, the curve of figure 77 is obtained. Three regions result from the dominance of R_p, then R_v, and finally R_s as the current density in the device increases from nanoamperes to kiloamperes per square centimeter.



$$\frac{V_L}{V_S} = \frac{Z_V}{Z_V + Z_S}$$

FIGURE 75. Voltage divider action between source impedance and clamp impedance.

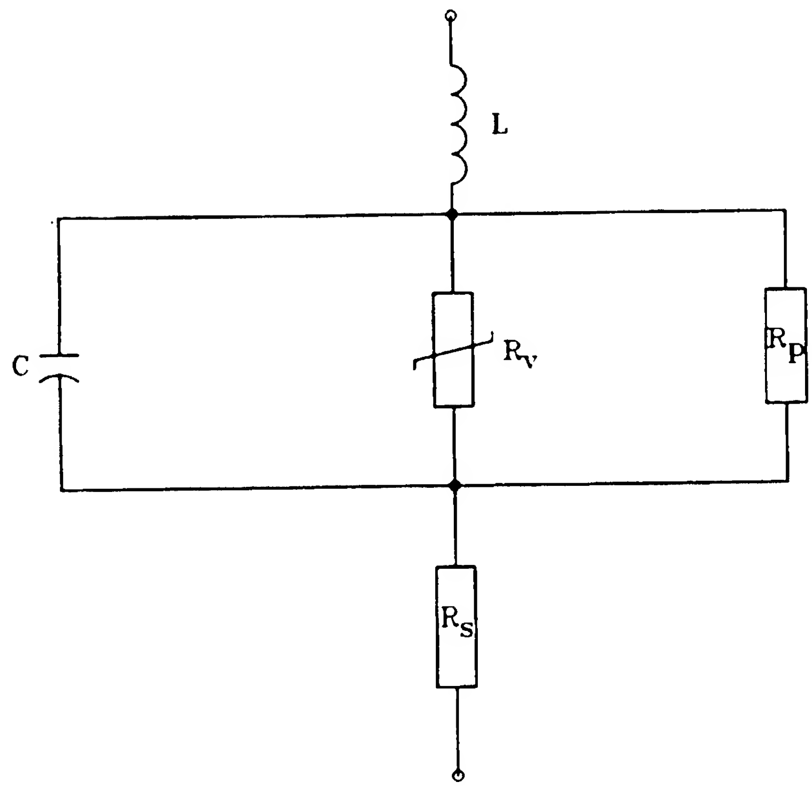


FIGURE 76. Equivalent circuit of a varistor.

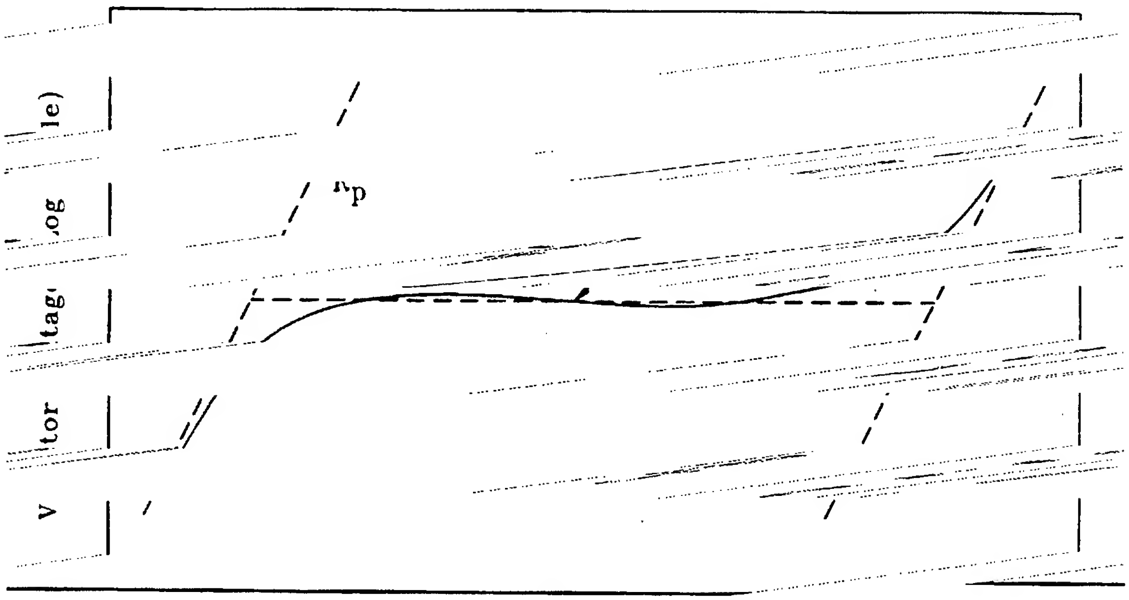


FIGURE 77. V-I characteristic of a varistor.

12.1.2.3 Advantages and limitations.

12.1.2.3.1 Advantages and limitations of crowbars.

12.1.2.3.1.1 Advantages and limitations of gas tubes and gaps. Crowbar gaps offer the advantages of high impedance (low capacitance) when nonconducting, large peak current and charge transfer handling capabilities, and availability in balanced pair (three-electrode) and coaxial (rf) configurations. The principal disadvantages or limitations of the crowbar gaps are:

a. The large *di/dt* and *dv/dt* associated with the switching action

b. Unsuitability for use in energized circuits, unless some means of extinguishing the arc is provided

c. The negative dynamic resistance when switching to the conducting state

d. The firing voltage tends to change with age

e. Slow response times, allowing passage of the pulse leading edge prior to crowbar action

The three-electrode gas tube accommodates surge protection on balanced circuits without converting the common mode surge into a differential mode surge. When two separate gas gaps are used, slight differences in the gaps may cause one gap to fire before the other. During the time between the two firings, a substantial differential mode surge is applied to the load circuit (figure 78). This problem can be avoided by using three-electrode gas tubes, where firing of the first gap causes firing of the second gap without delay.

The sharpness of the sparkover or turn-on produces high rates of change of current in the circuits. In the arrester circuit of figure 79, the gap discharges the impinging surges, but the magnetic field associated with the high di/dt induces a voltage in the loop adjacent to the clamp through mutual inductance. This induced voltage can add a substantial spike to the expected clamping voltage provided by the clamp.

The extinguishing limitation is associated with power-follow current after the surge discharge. In some ac circuits, depending upon the amplitude of the available current and device characteristics, the arc may not extinguish at a current zero-crossing. Additional means must therefore be provided to open the power circuit, if the crowbar does not provide self-clearing action. A combination of a gap with a current-limiting varistor has been used in the utility industry for this purpose. A circuit breaker, with manual or automatic resetting, can also be used to clear the power-follow current.

12.1.2.3.1.2 Advantages and limitations of solid-state crowbars. The generic advantages and limitations of crowbars that were discussed for gaps also apply to solid-state crowbars, except the voltage at which conduction starts can be lower and will be more consistent. In addition, compared to a gap the range of surge current handling capability is more limited, and they may be damaged by very large dv/dt ($> 5\ V/\mu s$). These devices are not normally recommended for use on the input of a filter.

12.1.2.3.2 Advantages and limitations of clamps.

12.1.2.3.2.1 Advantages and limitations of silicon diodes. The principal advantage of the avalanche diode is the possibility of achieving low clamping voltage and a nearly flat volt-ampere characteristic over its useful power range. Therefore, these diodes are widely used in low-voltage electronic circuits. Since the junction is very thin, the capacitance of an avalanche diode is appreciable (on the order of nanofarads). This device is thus used primarily in low-frequency, low-voltage applications. The device is not recommended for the HEMP barrier.

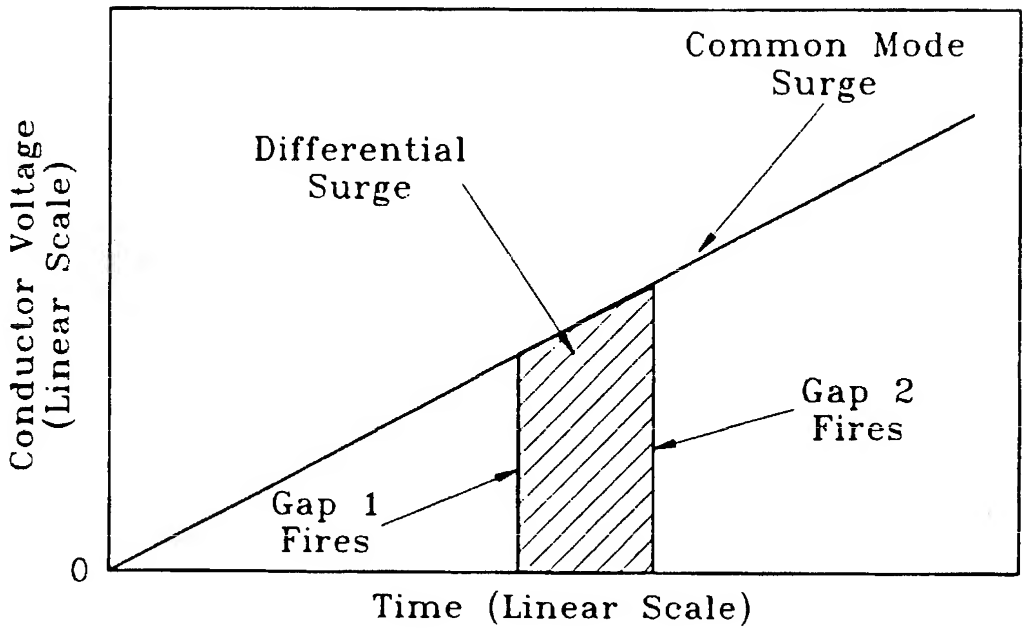


FIGURE 78. Differential mode surge created by different time to sparkover of two separate gas tubes.

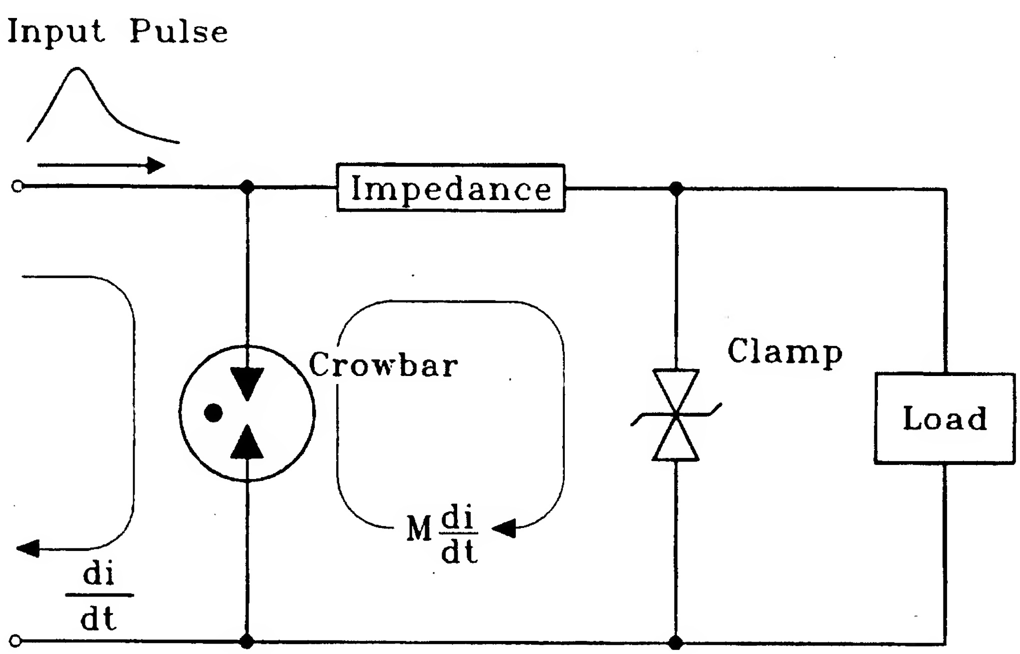


FIGURE 79. Mutual coupling between upstream and downstream loops.

12.1.2.3.2.2 Advantages and limitations of varistors. Varistors were initially based on silicon carbide mixtures, but metal oxide varistors have essentially replaced them. The major advantage of MOVs is their ability to dissipate large energies (on the order of kilojoules). Another advantage is the flexibility to produce devices with various shapes, aspect ratios, and total mass to tailor the geometry to the needs of the application. For fast-transient applications, the varistor material can be configured to minimize parasitic inductance by using coaxial configurations (signal applications) or four-terminal structures (power applications).

In its electrical performance, the metal oxide varistor exhibits negligible delay in changing its conductance. The "overshoot," if any, is associated with lead inductance or mutual coupling between the circuits upstream and downstream from the varistor connection. Proper attention to this situation is indeed essential in HEMP protection. The monotonic action of the varistor also avoids any disturbance of the type created by the firing of a gas tube, where fast rates of current changes can induce spurious voltages in adjacent circuits.

One disadvantage of varistors may be their relatively high capacitance. Hence, the varistor is not recommended for high-frequency applications. On the other hand, the capacitance of the device makes it an inherent low-pass resistor-capacitor filter, when combined with the characteristic impedance of the upstream transmission line. This filtering action effectively limits the rate of rise of any steep-front transient, so that the issue of "speed of response" of a varistor is rather moot.

Another limitation of varistors is their shift in the V-I characteristic after repeated transients. Varistors offered by electronic component manufacturers have long been characterized by a "pulse rating," acknowledging that the aging process is accelerated by using small varistors to clamp large (amplitude and duration) surges. On the other hand, varistors offered by manufacturers of utility-type arresters do not have this limitation, as long as a certain limit in the surge stress is not exceeded. The apparent contrast between the two application information bases was settled when electronic varistor manufacturers added an "indefinite" characteristic to their pulse rating curves (figure 80).

12.1.2.4 Device selection criteria. Two steps are involved in selecting a device. First, the type of device (crowbar, clamp, hybrid) most suited to the qualitative needs of the protection is determined. Secondly, specific device ratings must be chosen. The advantages and limitations discussed above provide guidance in selection of the type. Selection of ratings is a systematic process, where the basic requirements cited in 12.1.2.2.3 provide the mandatory criteria.

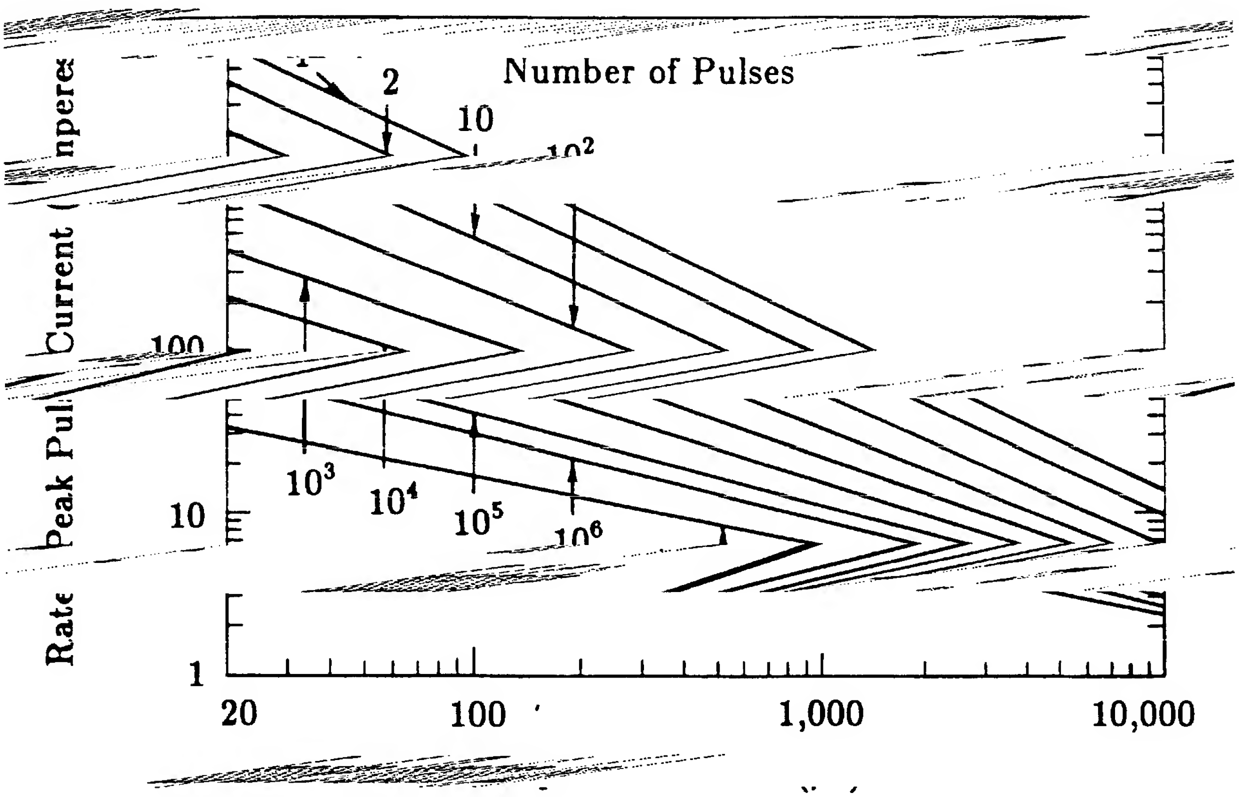


FIGURE 80. Pulse rating curves with "indefinite" rating added.

12.1.2.4.1 Crowbar selection criteria. The arc voltage of a gap crowbar or the on-state voltage of a solid-state crowbar is generally low, and it is therefore not an essential criterion for selection within the family of crowbars. The most significant criteria are the sparkover voltage characteristics, the ability of the device to carry the expected surge current (or charge transfer) with minimal degradation, the ability (or inability) of the device to return to the off state after the surge, and the effect of the device on the protected circuit.

12.1.2.4.2 Clamp selection criteria. The V-I characteristic that describes the clamping function and the energy dissipation rating are important in selecting a clamp. For a successful application, however, other factors, discussed in detail in the information available from manufacturers, must also be taken into consideration:

a. Selection of the appropriate nominal voltage for the line voltage of the application. Under competitive pressures, some designers are attempting to "improve" the protec-

tive ability of a clamp by selecting a low-voltage rating for the device. This practice can seriously jeopardize reliability (see 12.1.2.7.2).

b. Selection of the current-handling capability (including consideration of the source impedance of the surge, the wave shape, and the number of expected occurrences).

c. Proper installation, with minimum lead length, in the circuit. Depending on the specific application (high power circuit, low power circuit, signal lines) the lead configuration and installation practices must be taken into account. The performance of an excellent device can be negated by improper installation.

12.1.2.5 Hybrid series combinations.

12.1.2.5.1 General. Combining various surge protective devices is often an effective approach. For instance, spark gaps connected in series with varistors may work better than gaps alone, or than varistors alone. The series combination of a gap with a varistor alleviates some of the inherent disadvantages of each of these devices, while maintaining their essential advantages.

As a first example, a gap used in an energized circuit has the problem of power-follow, where the current supplied by the power system after the surge has caused conduction may be high enough to prevent the arc from extinguishing. Adding a varistor in series limits the follow current without excessively increasing the protective voltage and allows the arc to extinguish.

Conversely, the addition of a gap in series with a varistor alleviates three disadvantages the varistor would have if used alone for some applications:

a. The relatively high capacitance of the varistor, which can be objectionable for high-frequency circuits, is negated by the low series capacitance of the spark gap.

b. Concerns over long-time stability of a varistor under steady exposure to the power system voltage are reduced by the disconnecting effect of the gap.

c. The standby current of the varistor in a power system, which may be excessive if the clamping voltage is set low (especially with silicon carbide), is eliminated.

However, there is a price to pay for the advantages. Compared to a simple gap, the series combination is limited by the current handling capability of the varistor which must carry the surge and follow currents. Furthermore, the effective clamping voltage of the series combination is the sum of the varistor clamping voltage and the arc voltage of

the gap. Compared to a simple gap, the series combination introduces two undesirable elements in the response of the gap: volt-time delay in initial sparkover and the occurrence of a sharp sparkover, which can be the source of interference in nearby circuits.

Another example of the mitigation of individual device disadvantages by a series combination of devices is the addition of a low-capacitance diode in series with a high-capacitance silicon avalanche diode. In ac circuits, this approach has been used by placing a silicon avalanche diode across a bridge of low-capacitance diodes (reference 12-6). However, compared to a silicon avalanche diode used alone, the addition of a low-capacitance diode in series can introduce some overshoot as a result of the switching time of the diode.

12.1.2.5.2 Basic design and application considerations. The two series combinations here discussed address different concerns:

a. Use of a series combination instead of a gap alone – If analysis shows that the follow current at the point of connection of the gap would exceed the gap capability, then either another gap must be selected or a varistor must be added in series. The existence of this unacceptable situation can be determined by inspection of the gap specifications: dc holdover in the case of telephone circuits (reference 12–7), or nominal alternating discharge current. The selection of the additional varistor would then be based on two considerations:

   - The standby current of the varistor (at the temperature resulting from the surge event) must be low enough to allow clearing by the gap.
   - The varistor must be capable of handling the surge current without adverse effects.

b. Use of a series combination instead of a varistor alone - The prime motivation could be rooted in three concerns:

   - The intrinsic capacitance of the varistor in a high-frequency, high-power circuit would create unacceptable insertion losses.
   - The nonlinear characteristics of the varistor in a frequency-spectrum critical system would introduce unacceptable harmonics.
   - Long-term exposure to a power system environment may result in a slow drift in the V-I characteristics, with adverse effects on reliability.

12.1.2.6 Hybrid parallel combinations.

12.1.2.6.1 General. The circuit design in figure 81 combines the advantages of two types of transient protective devices, without adding disadvantages. In figure 81, the gap provides a high-energy (charge transfer) diverting path, but passes significant voltage. The silicon avalanche diode provides a low clamping voltage with fast response, but has limited current handling capability. The impedance Z creates a voltage drop that promotes the sparkover of the gap, so that not all the surge current has to be diverted by the diode.

It must be recognized that these devices may interact detrimentally. It must also be noted that there is a fundamental difference in behavior of gas tubes and solid-state clamping devices (varistors and diodes). It is necessary to take into consideration the impinging surge voltage as well as the corresponding available surge current (reference 12–8). The following provides basic information on the requirements for designing such a hybrid combination.

12.1.2.6.2 Example of the principle of coordination. Figure 81 illustrates an example of two-step protection involving a spark gap in the first step, an avalanche diode in

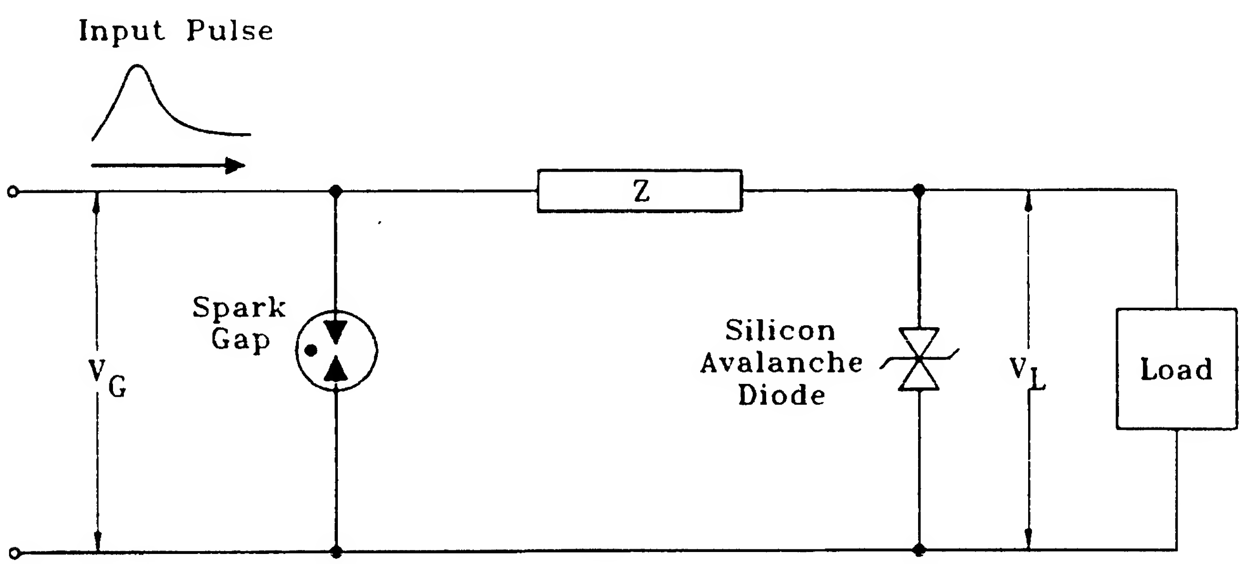


FIGURE 81. Hybrid parallel combination of ESAs.

the second step, and an impedance separating the two devices. In signal circuits, the separating impedance may be a resistance, but in power circuits inductors are used because the power loss associated with a resistance may be unacceptable.

Assume that a surge is impinging on the input terminals of the hybrid ESA. No current flows through the gap during the initial part of the rise time of the surge, before the gap conducts. Some current, therefore, flows through *Z* and the parallel combination of the diode and the protected load. The voltage V_L across the load will immediately rise to the clamping voltage of the diode.

The voltage V_L will not significantly exceed the diode clamping voltage if the connecting leads of the diode are kept as short as possible, i.e., less than a few centimeters. Meanwhile, the voltage V_G across the gap is equal to the sum of the voltage drop across Z and the clamping voltage which is related to the value of the current through the diode.

If the impedance of *Z* is sufficiently high at the apparent frequency of the input current waveform, the resulting voltage V_G will fire the gap. Current will flow through the gap, relieving the diode of the need to continue diverting the high surge current. Should the spark gap be replaced by a gapless surge suppressor, its discharge voltage must be exceeded by the same voltage drop across *Z,* added to the discharge voltage of the diode.

Several parameters must be considered for this hybrid to operate as intended. If the necessary coordination is not designed into the circuit, the diode may fail because the relief expected from the spark gap does not occur before excessive energy is deposited in the diode.

The parameters to be considered are the peak value and rate of rise of the surge current, the value of the impedance *Z* separating the two surge suppressors, the clamping voltage of the diode, and the sparkover voltage of the gap.

a. Surge currents and voltages - The current delivered by the surge source and diverted through the surge suppressor is specified in MIL-STD-188-125; the voltages resulting from the characteristics of the protective devices are the dependent parameters.

b. Series impedance - The series impedance, shown as *Z* in figure 81, separates the spark gap and silicon avalanche diode surge suppressor. Whether it is a discrete component or the impedance of the wiring, it must ensure that the gap fires before the power or energy rating of the diode is exceeded.

c. Relative values of voltages – If the sparkover voltage of the gap is very large compared to the clamping voltage of the diode, coordination is difficult to obtain because the

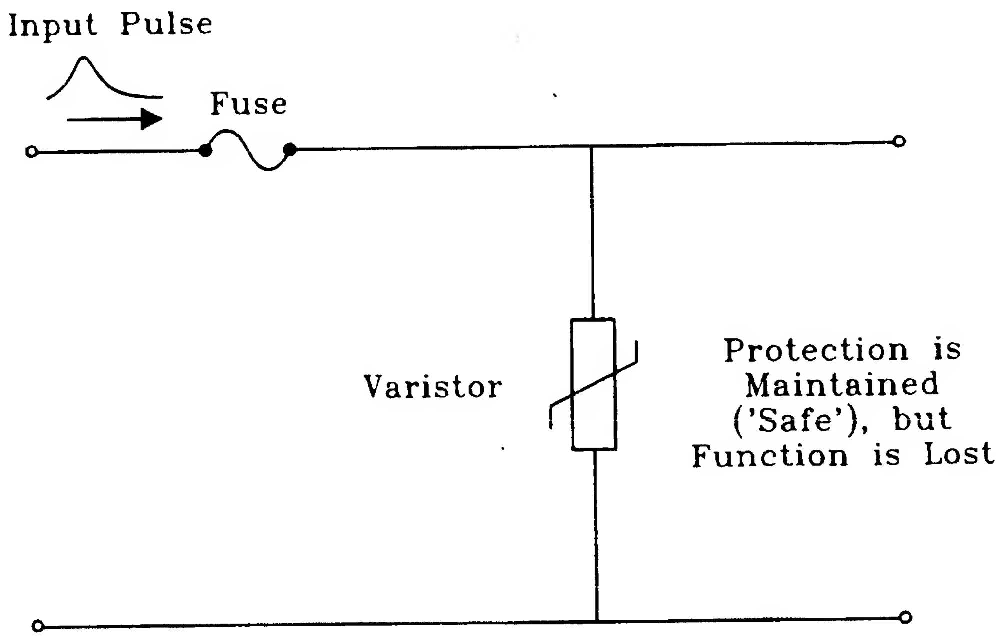
voltage drop in Z must be large to raise the voltage V_G to the firing level. Coordination is achieved if the voltage drop in Z during the initial current rise in the diode, added to the discharge voltage (clamping voltage), is sufficient to cause sparkover of the gap, and if the diode will tolerate a steady state current that produces a voltage V_G just below the sparkover voltage of the gap.

For example, with the diode clamping at 500 V and a sparkover voltage of 2000 V for the gap, a voltage of 2000 − 500 V = 1500 V must be developed across Z to cause sparkover and start the current flow in the gap. The required 1500 V will be obtained if, and only if, the $L\, di/dt$ product attains that level. Therefore, the rate of rise of the current and the amplitude of the surge must be defined. There is a risk that relatively slow or low-amplitude current surges may not produce the required coordination if the design was based only on transients producing the maximum stress, i.e., minimum risetime and maximum amplitude, rather than the complete range of possible stresses. This situation has been described as having a blind spot in the performance (reference 12-9). Test procedures that include a progressive increase of the test stress, such as appendix B of MIL-STD-188-125, will avoid this pitfall.

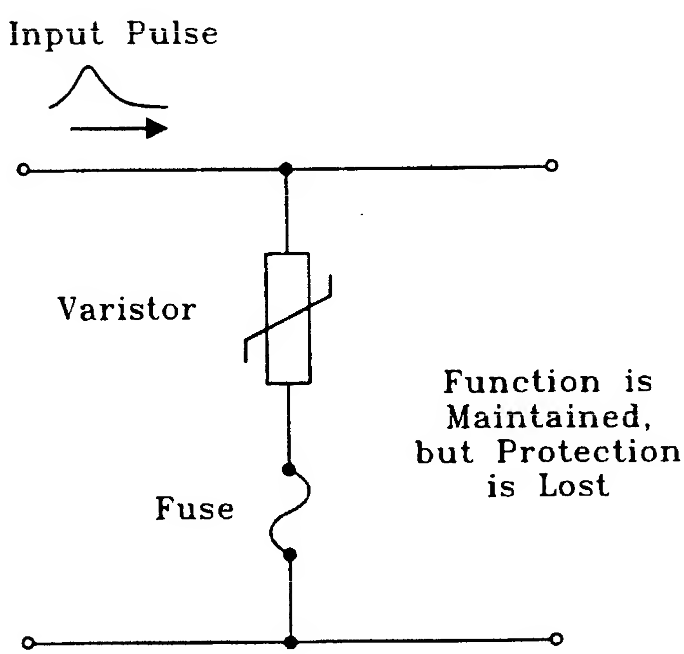
12.1.2.7 Failure modes.

12.1.2.7.1 Device failure modes. In a clamp, because more energy is deposited in the device, the current-handling capability is an important parameter in the design of a protection scheme. When surge currents in excess of the protective device capability are imposed by the environment, the circuit can generally be protected at the price of failure of the protective device in the short-circuit mode. However, if substantial power-follow currents can be supplied by the power system, the fail-short protective device generally terminates as fail-open when the power system fault in the failed device is not quickly cleared by a series overcurrent protective device (fuse or breaker). With the failure mode of a suppressor being of the fail-short type, the system protection can be provided with fuses in line as shown (figure 82a), provided the fuse is in the line as illustrated. The practice of fusing the varistor, as shown in figure 82b, risks the loss of HEMP protection and should not be used. Another useful approach might be the addition of an alarm to the visible indication of fuse failure presently required in consumer protective devices (reference 12-10).

12.1.2.7.2 Excessively low clamping voltage versus reliability. The inherent characteristics of a clamp and the constraints of the application must be matched to obtain optimum long-term reliability, while providing effective surge protection (reference 12–11). A low clamping voltage can shorten the life of the device. There is, therefore, a point at which the incentive for low clamping voltage becomes counterproductive. It is very



a. Function at risk to maintain protection.



b. Protection at risk to maintain function.

FIGURE 82. Examples of fuse protection against ESA failure.

important that users recognize this issue to resist proposals of protection schemes at low levels but at the risk of questionable long-term reliability.

Three phenomena act separately, but with additive effects, toward decreasing the service life of clamps if they are selected with excessively low clamping voltage:

a. Unexpected momentary overvoltages of the power system

b. Equilibrium between heat dissipation and heat generation after a surge

c. Large increase in the number of current pulses drawn by the clamp

These effects have been recognized and documented for varistors; proper application design can eliminate disappointing performance. For avalanche diodes, there is less documentation.

12.1.2.7.2.1 Standby conditions. The first phenomenon of concern is the effect of line voltage on the current drawn by a varistor under standby conditions. Power systems are expected to operate within specified limits of low and high voltage, because some excursions from nominal conditions are unavoidable. Typical limits are set by voltage rating standards (reference 12–12), but severely abnormal conditions can occur, leading to momentary overvoltages beyond the standard limits. A varistor subjected to these momentary overvoltages will draw a relatively large peak current at the power frequency. If the amplitude is high and the duration of the event long, overheating of the device may occur. This overheating can produce thermal runaway and destruction or significant consumption of the rated life of the device. Because small increases in the line voltage peaks will result in large increases of current peaks drawn by the device when the overvoltage endures, the increased energy dissipation raises the device temperature. The higher temperature produces a shift in the V-I characteristic, which further increases the current drawn by the varistor; hence the possibility of thermal runaway.

12.1.2.7.2.2 Thermal equilibrium after a surge. The second phenomenon of concern is also related to thermal runaway, but under surge conditions rather than for the momentary overvoltage conditions just discussed. When a surge current passes through a varistor, the energy dissipated by this current produces heating of the bulk material. Because the varistor has a positive temperature coefficient, the standby current increases with the device temperature. Following a surge current, the current through the device associated with the line voltage (standby current) is then increased, which in turn produces an increase in heating. This heat must be dissipated by radiation or conduction from the device body when the temperature of the body increases. A dynamic thermal balance occurs between increased heat dissipation and increased heat generation by the

standby current. A varistor selected for a low clamping voltage cannot absorb as large a surge energy as a varistor with higher clamping voltage before thermal runaway occurs.

Manufacturers' ratings of varistors aimed at selection of a nominal voltage take into consideration the thermal balance under surge conditions, as described in test specifications (reference 12–13). If the actual environment does not exceed the expected surge stress for this selection, all is well. However, if the surge environment is not precisely known, a varistor with a reasonably higher clamping voltage should be selected for greater reliability.

12.1.2.7.2.3 Consumption of pulse rating. The third phenomenon of concern is the number of surges that a varistor can absorb before reaching its total pulse rating. This number decreases when the amplitude or duration of the surges increases. For a given environment, the number of surges above a stated level increases steeply as the stated level is lower. For instance, in 120 Vac power systems, the relative increase in the number of surge occurrences between 600 V and 350 V is about 6 times (reference 12–14). Therefore, even relatively low amplitude surges will expend the rating of a varistor with unnecessarily low clamping voltage at a faster rate than that of a varistor with only slightly higher clamping voltage.

Furthermore, studies have revealed surges of long duration, in the millisecond range, with amplitudes on the order of 200 to 250 percent of the power frequency peak voltage. Although their frequency of occurrence is lower than that of shorter surges, the total heat dissipation in a varistor responding to such a relatively low amplitude can be substantial because of the long duration. The heating will bring into play the phenomena discussed above, as well as an undue consumption of the pulse rating of the device. On the other hand, a varistor selected to intervene only above twice the normal voltage peak will be less exposed to this unnecessary consumption. This situation should be kept in mind when selecting device characteristics.

12.1.2.8 Packaging and mounting. Component surge-protective devices such as gaps, varistors, or avalanche diodes are used by original equipment manufacturers for incorporation into the circuitry of their products. In contrast, packaged ESAs are applied by the end-users for incorporation into their installations. These packages can in fact consist of a single component provided with a suitable housing and terminals, or it can consist of a more complex hybrid or polyphase configuration. Packaging of an ESA accomplishes two desirable goals: convenience of insertion by the user and coordination of the design for multiple-component protective schemes.

Unfortunately, this packaging sometimes intentionally obscures the principles of protection being offered, making an evaluation of performance claims difficult. One reason for

the frequent lack of information on the performance of the packages being offered is a lack of standards that would provide manufacturers and users with realistic and uniform application requirements. Component protective devices have the benefit of presently available test specification standards (references 12–7, 12–13, 12–15, and 12–16), but standards-writing groups have not yet completed their projects on packaged suppressors.

12.1.3 Filters.

12.1.3.1 Basic principles. In general, only a limited frequency spectrum is required to carry signal and power currents on cables entering fixed, ground-based facilities. Thus, the energy from transients induced by HEMP, lightning, or other sources of electromagnetic interference can be greatly reduced by using a spectral limiter or filter. A filter is a linear protection device that limits the frequency spectrum allowed to pass on signal and power lines entering the electronic equipment. Filters are used to pass signals or currents at certain frequencies to the load, while unwanted frequencies are either shunted to ground or reflected back to the source.

Filters can be classified by the band of frequencies allowed to pass with little or no attenuation. Low-pass filters pass currents having frequency components from dc to a specified cutoff frequency. The cutoff frequency or 3 dB point—the point where half of the power is passed to the load—separates the passband from the rejection band. Bandpass filters pass currents within a limited band of frequencies defined by two cutoff frequencies—the lower and upper 3 dB frequencies—and reject currents whose frequencies are in the upper and lower stop bands. The filter bandwidth is the difference between the upper and lower cutoff frequencies. High-pass filters allow passage of spectral components above the 3 dB point, but reject currents at frequencies below cutoff. Figure 83 shows the frequency response curves for low-pass filters and for bandpass filters with a center frequency f_o.

Because they are made from reactive components, most filters absorb little transient energy. They reflect most of the energy by providing a high input reactance (choke input) or a low reactance to ground (capacitive input) which constitutes an impedance mismatch for the transmission line attached to the input terminals. Thus, when reactive filters are used, the reflected energy may cause HEMP stresses to increase at other locations, potentially creating new vulnerabilities. As a general design rule, it is always useful to understand where the reflected energy will go when a filter is added. Even when the filter is used at a major facility shield interface, it is desirable to avoid shunting large currents onto the shield in a manner that will stress large areas of the shield surface. A single penetration entry area avoids this problem (see section 12.3.7).

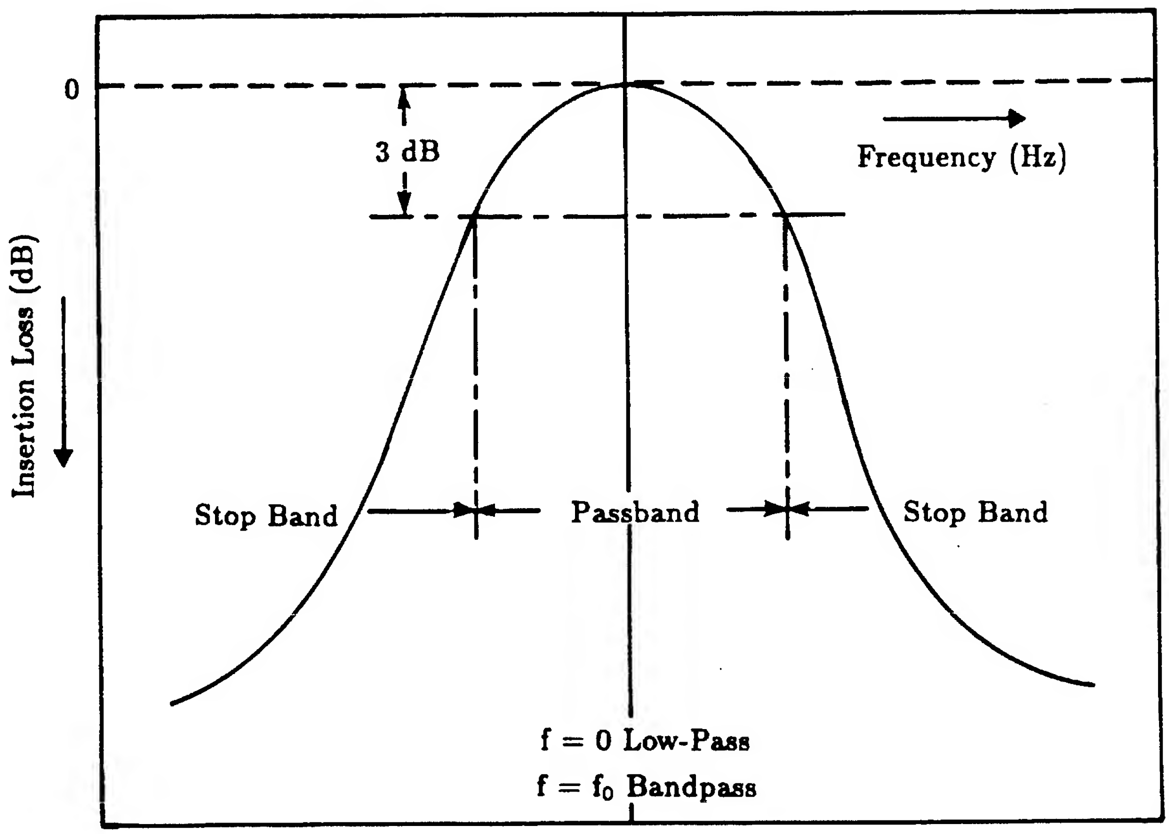


FIGURE 83. Insertion loss of filters.

When a short pulse of current such as that produced by HEMP or lightning appears at the input of a linear filter, the output from the filter is a damped sine wave (essentially identical to the impulse response of the filter). The output may also include a reduced amplitude replica of the input pulse. This impulse response is determined by the values of inductance and capacitance in the filter. Reactive filters that are operated with high-impedance loads may actually amplify the signal at the resonance frequencies.

Dissipative (lossy) filters convert part of the energy in the rejection band to heat. Some use capacitors with a lossy dielectric or a series resistance. Another type of lossy filter takes advantage of the increasing resistance loss versus frequency characteristics of materials such as ferrite compounds and carbonyl-iron mixtures. Dissipation outside the passband damps the oscillatory impulse response and can prevent gain under mismatched conditions.

Because power line filters often use large capacitances, they may draw large reactive (capacitive) current from the power line, even under no-load conditions. This problem is more common at 400 Hz power frequencies than 50 Hz or 60 Hz. Many suppliers of large power line filters address this problem by adding a power factor correction coil to the output of the filter. In addition, the insulation in filter capacitors can withstand only 3 to 5 times the rated operating voltage. Thus filters tend to fail due to dielectric overstress.

12.1.3.2 Filter design and operation. Capacitors, inductors, isolation transformers, quarter-wave tuning stubs, ferrite beads, and common-mode rf chokes are some of the devices used to implement filters for HEMP protection. The physical means by which the filter limits the frequency range of currents on the treated conductor fall into two broad categories: dissipative (energy absorbing) and nondissipative (energy reflecting) filters.

Lumped element filters, consisting of various combinations of capacitors and inductors, are of the nondissipative type. At the passband frequencies, power is transferred to the load and, in the rejection band, reflection of the undesired spectral components takes place due to the reactive input impedance of the filter. Reactive, nondissipative filters reflect the unwanted transient energy back to the source. This can result in spurious transmission line resonances which will degrade the rejection band or even the passband characteristics of the filter.

Filters may be used on power, control/signal, and data lines at their point-of-entry through the shield. The filters suppress the high frequency content of incident transients, and allow the intended signal or power frequencies to pass without excessive loss. Filters in the facility-level HEMP barrier must be selected to tolerate the HEMP-induced voltages and currents incident upon them from the external lines. The open-circuit voltages are

very large. Therefore, if a series inductance is used at the input terminals, it must be designed to tolerate large open-circuit voltages (see 12.1.3.5 below).

12.1.3.3 Insertion loss. The insertion loss of a filter depends on the source and load impedance. Insertion loss measurements obtained with the test method in MIL-STD-220 (reference 12–17) are only a qualitative measure of power line filter performance. The insertion loss data measured in this manner cannot be used to determine the actual response of a filter to the pulse specified in MIL-STD-188-125.

12.1.3.3.1 Power line filters. Power line filters should be tested under full-load conditions at the factory, using an extended-range buffer network. The test load should cover the range of impedances that the filter will experience at the installation where it will be installed.

The calculated insertion loss of a capacitive-input filter is shown in figure 84 for three combinations of the source impedance R_o and the load impedance R_L in a test circuit. These conditions are as follows:

a. $R_o = 50\ \Omega$ and $R_L = 50\ \Omega$; this is the test condition specified in MIL-STD-220.

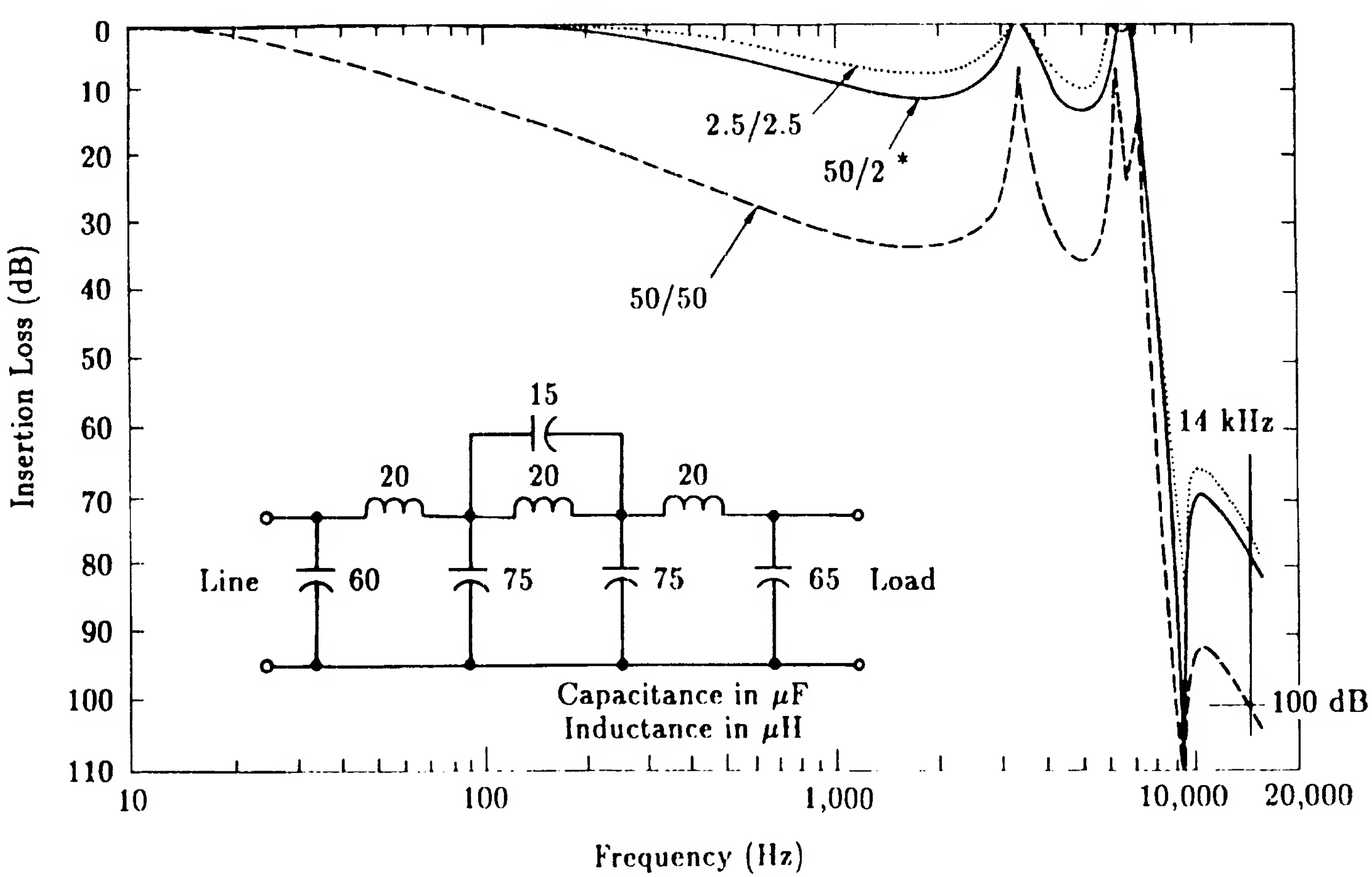
b. $R_o = 2.5\ \Omega$ and $R_L = 2.5\ \Omega$; this is the load impedance at full load on a 250 V filter rated for 100 A.

c. $R_o = 50\ \Omega$ and $R_L = 2\ \Omega$; the source impedance is typical for a short pulse generator, and the load impedance is the nominal MIL-STD-188-125 acceptance test load.

The insertion loss in the 50 Ω/50Ω circuit just meets the requirements for 100 dB at 14 kHz. In the 2.5 Ω/2.5Ω circuit, the insertion loss at 14 kHz is reduced to 75 dB, and the performance in the acceptance test circuit is similar. Note also that the insertion loss at 60 Hz in the 50 Ω circuit is 9 dB. This is a ramification of the power filter design in which the passband is designed for 60-Hz loads, while the rejection band is designed to 50 Ω insertion loss requirements.

12.1.3.3.2 Signal line filters. Signal line filters should also be tested under full-load conditions at the factory. The test loads should cover the range of impedances that the filter will experience at the installation where it will be installed. An appropriate method should be employed when testing the signal line filter under full load.

It is recommended that filter installations be designed for ease of servicing and repairing filter components. In addition, HEMP hardening filter requirements should be standardized to ease initial and replacement acquisition requirements.



* 50/2 Denotes $R_o = 50\Omega$ and $R_L = 2\ \Omega$

FIGURE 84. Insertion loss of capacitive-input filter for various source and load impedances.

12.1.3.4 Capacitive-input filters. Filters with shunt capacitors at their input terminals reduce the rate of rise of the voltage because the input capacitance charges with an *RC* time constant, where *R* is the source resistance of the external line and C is the input capacitance of the filter. If this time constant is large enough, the rate of rise may be so small that the surge arrester fires near its static firing level. Thus, both the overshoot and the overstress are eliminated or reduced. Furthermore, the filter and the wiring need not tolerate high voltages, since these voltages are not allowed to develop.

One often-used class of power-line filter is specified to have 100 dB insertion loss in a 50 Ω/50 Ω circuit at 14 kHz and less than 1 percent voltage drop through the filter at the power frequency (60 Hz). In such a filter, the total series inductance is typically 60 μH, so that the 60-Hz series reactance is 0.023 Ω, which will produce 2.3 V drop with 100 A through the filter. Thus, the filter meets the voltage drop requirement for 100 A, 250 V service. The shunt input capacitance of this filter is so large that it prevents a surge arrester from conducting when the short pulse of MIL-STD-188-125 is applied. However, some current diversion by a surge arrester is necessary to meet the residual current requirements specified in MIL-STD-188-125. Also, the characteristic impedance of the filter is of the order of 0.5 Ω. Hence, the filter will be severely mismatched in the 50 Ω circuit used in the MIL-STD-220 insertion loss measurement.

In the following subparagraphs, the transient responses of a typical 100 A, 250 V power line filter are described for the MIL-STD-188-125 direct injection current pulses. These responses were computed with a simple time-domain circuit analysis program. They illustrate the behavior of the filter input voltage which is important in evaluating surge arrester performance. They also show the load current, which is important in evaluating the filter's ability to meet the residual stresses permitted by MIL-STD-188-125.

12.1.3.4.1 Short pulse response of filter. The response of the filter of figure 84 to the 4000 A exponential pulse, as specified in MIL-STD-188-125, from a 50 Ω source was calculated (reference 12–18). The circuit block diagram is illustrated in figure 85. The source impedance R_o is 50 Ω and the load impedance R_L is 2 Ω. The input current I_i, the input voltage V_i, and the load current I_L computed for the filter are shown in figure 86.

The voltage V_i across the filter input terminals, shown in figure 86b, reaches a peak value of less than 50 V. This is well below the voltage required to activate a power line surge arrester. Hence, a surge arrester placed across the filter input terminals will never be actuated by the test pulse. This is because the total charge delivered to the filter capacitors by the 4 kA current pulse is too small to charge the capacitors to surge-arrester firing voltages. If the entire charge in the current impulse, which is 2.9 x 10^{-3} C, is delivered to the 60 μF input capacitor, the capacitor will be charged to a voltage of

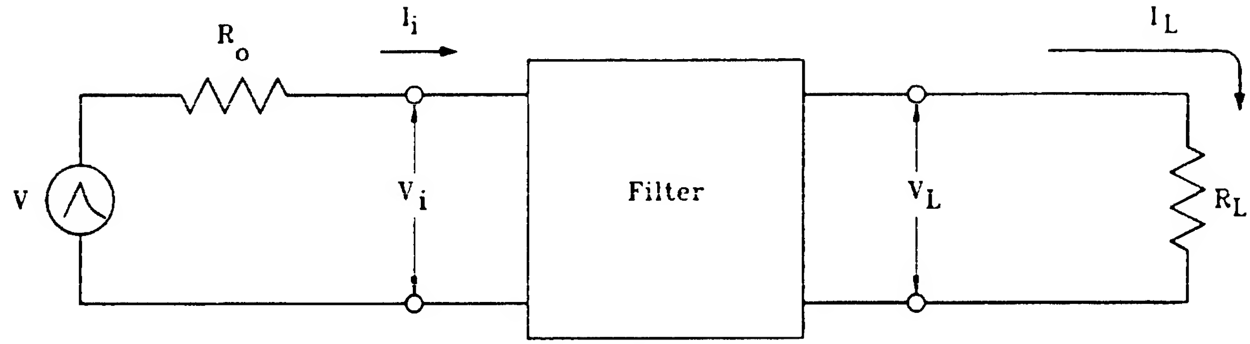
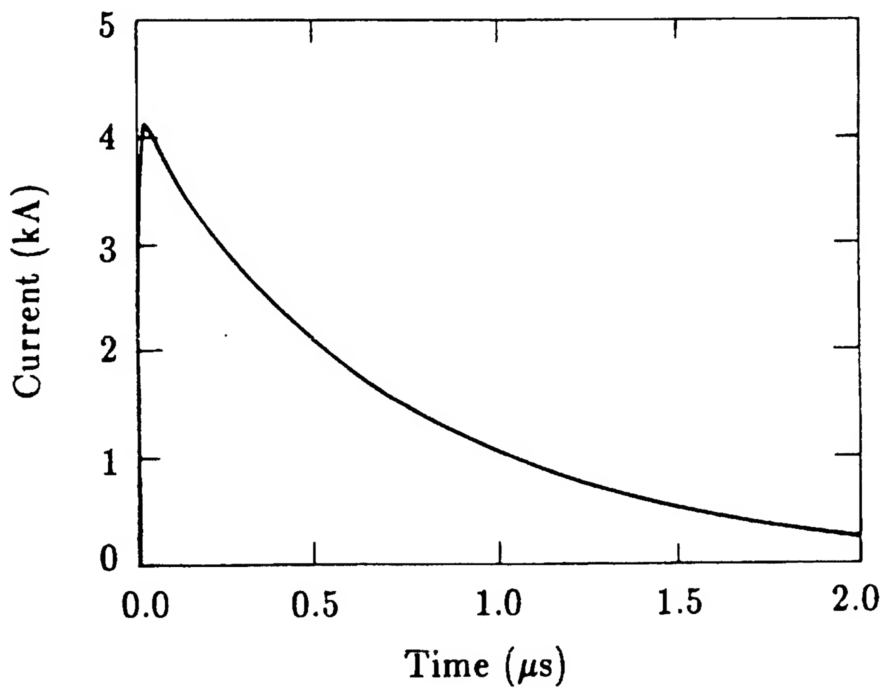
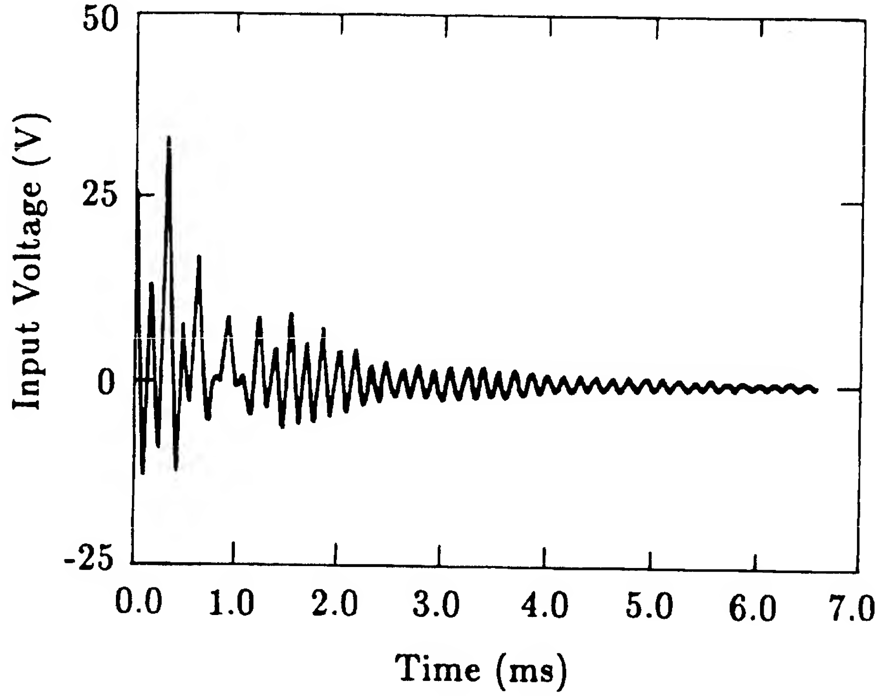


FIGURE 85. Acceptance test circuit.

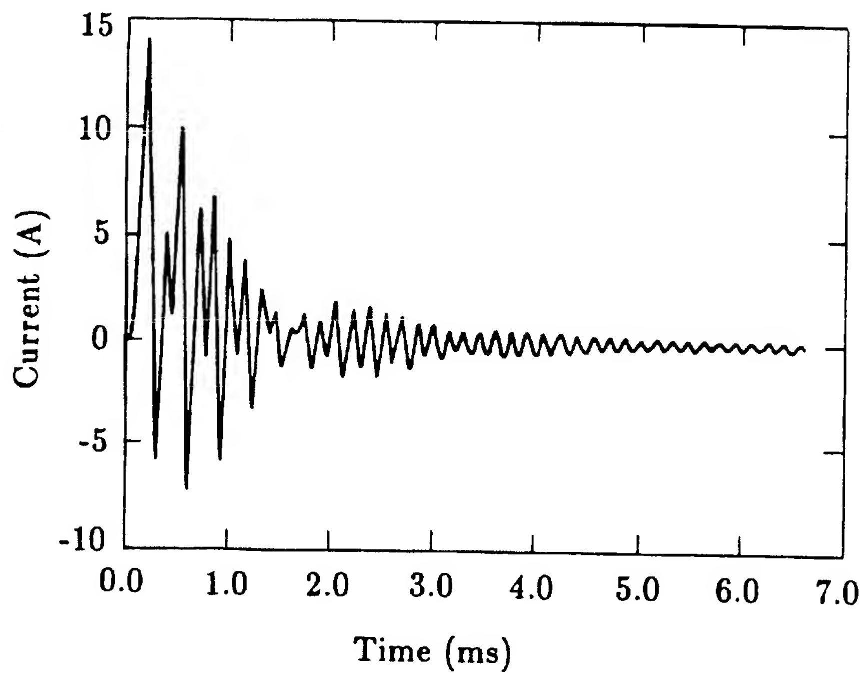


a. Source current.

FIGURE 86. Capacitive-input power line filter-short pulse response (R_o = 50 Ω, R_L = 2 Ω).



b. Input voltage.



c. Load current.

FIGURE 86. Capacitive-input power line filter-short pulse response (R_0 = 50 Ω, R_L = 2 Ω) (continued).

48 V. Any stray inductance of the filter terminals and input circuit has been neglected The outcome of the analysis could change if the capacitor had an initial charge due to a power-on condition.

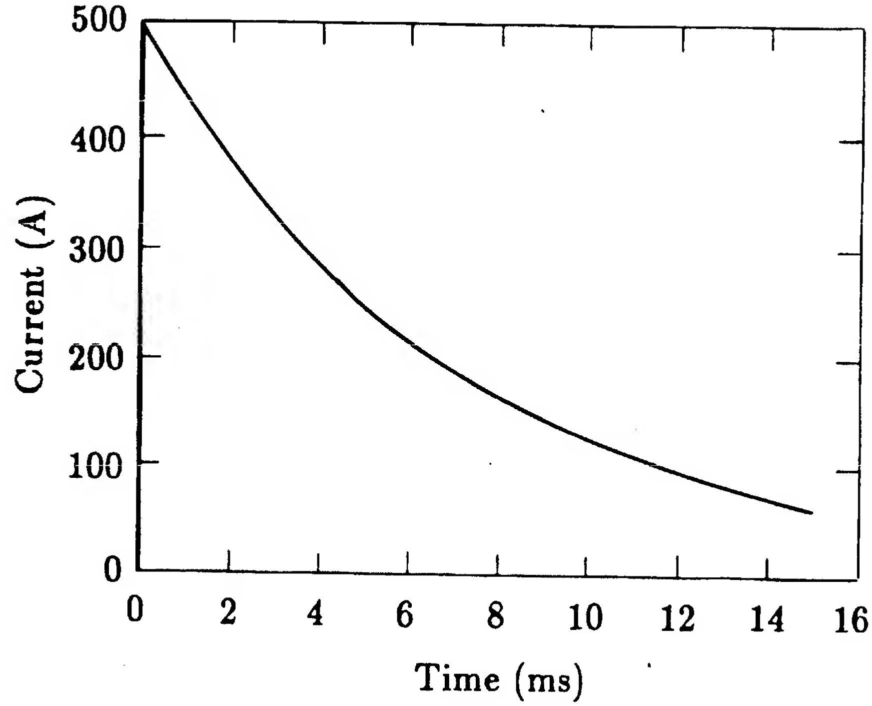
The current I_L delivered to the 2 Ω load is shown in figure 86c. This oscillator impulse response has a peak current of 14 A, which is well above the 10 A allowed by the standard. Since the output current is the impulse response of the filter (because the time constant of the filter is much greater than the pulse width), it will be necessary to reduce the impulse of the input with a surge arrester and series inductance to reduce the peak current to 10 A.

12.1.3.4.2 Intermediate pulse response. The responses of the filter to the intermediate pulse (500 A peak short-circuit current, from a 50 Ω source) are shown in figure 87. The input current I_i delivered to the terminals of the filter is shown in figure 87a for a 2 Ω load on the output terminals of the filter. This current reaches 90 percent of the peak current within the first microsecond, reaches the 500 A peak at about 3 μs, and decays to half peak value at 5 ms. The filter oscillation is also evident in the input voltage and load current waveforms in figures 87b and 87c.

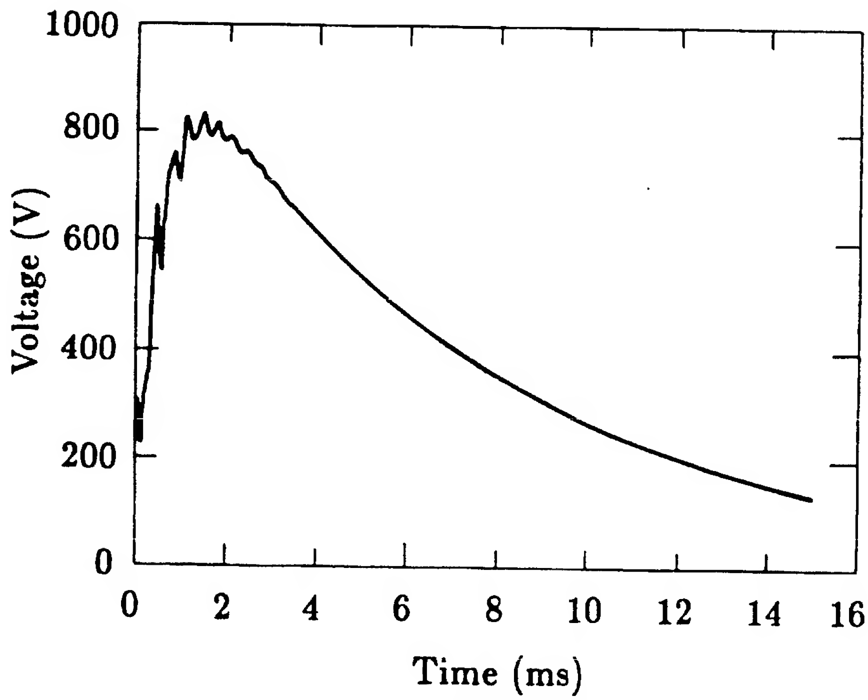
Because the decay time of the pulse is comparable to the filter time constant, much of the intermediate pulse passes through the filter. The charging time constant for the filter shunt capacitance with the 50 Ω source impedance and the 2 Ω load is 0.53 ms. The current I_L through the 2 Ω load, shown in figure 87c, illustrates this behavior. The rise time of this current has been lengthened to about 0.7 ms by the filter, but the decay time is essentially that of the source. The load current amplitude also greatly exceeds the 10 A allowed by the standard for the short pulse. The peak current through the load is greater than 400 A, and the peak input voltage is about 800 V.

A 250 V MOV would clamp this voltage to about 600 to 700 V, but a current of 300 to 350 A would still flow in the load. The 800 V peak voltage might not fire a spark-gap surge arrester on a 250 V line. Thus protection against the intermediate pulse will require a strategy different than that implemented by this filter. This strategy is described in 12.3.1.3.

12.1.3.4.3 Long pulse response. The filter is transparent to the long pulse. The response of the filter to the long pulse of MIL-STD-188-125 was computed for a source impedance of 3 Ω and a load impedance of 2 Ω.

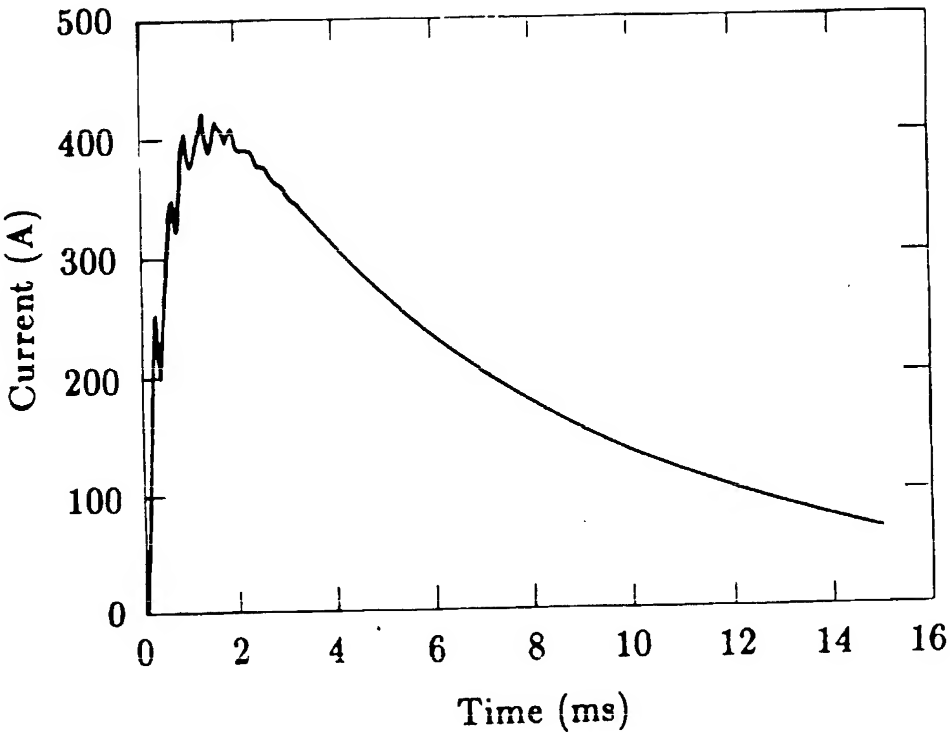


a. Input current.



b. Input voltage.

FIGURE 87. Capacitive-input filter response to intermediate pulse (R_o =50 Ω, R_L = 2 Ω).



c. Load current.

FIGURE 87. Capacitive-input filter response to intermediate pulse (R_0 = 50 Ω, R_L = 2 Ω) (continued).

The first two seconds of the responses are shown in figure 88. The input and load currents are identical to three significant figures, and the input voltage is very nearly the output current multiplied by 2 Ω, the load impedance.

The 400 V input voltage of the filter will not activate either MOV or spark-gap surge arresters on 250 V lines. Therefore, the long-pulse threat to the system is not alleviated by a surge arrester/filter combination. Nevertheless, the 200 A current flowing into the system for -100 s is likely to be intolerable by many systems. Some methods of interrupting the long pulse are given in 12.3.1.4.

12.1.3.5 Inductive-input filters. To ensure that the surge arrester is activated by the short pulse, one may consider using a filter with a series inductance at the input. The insertion loss of a typical 100 A, 250 V, inductive-input filter for power service is illustrated in figure 89.

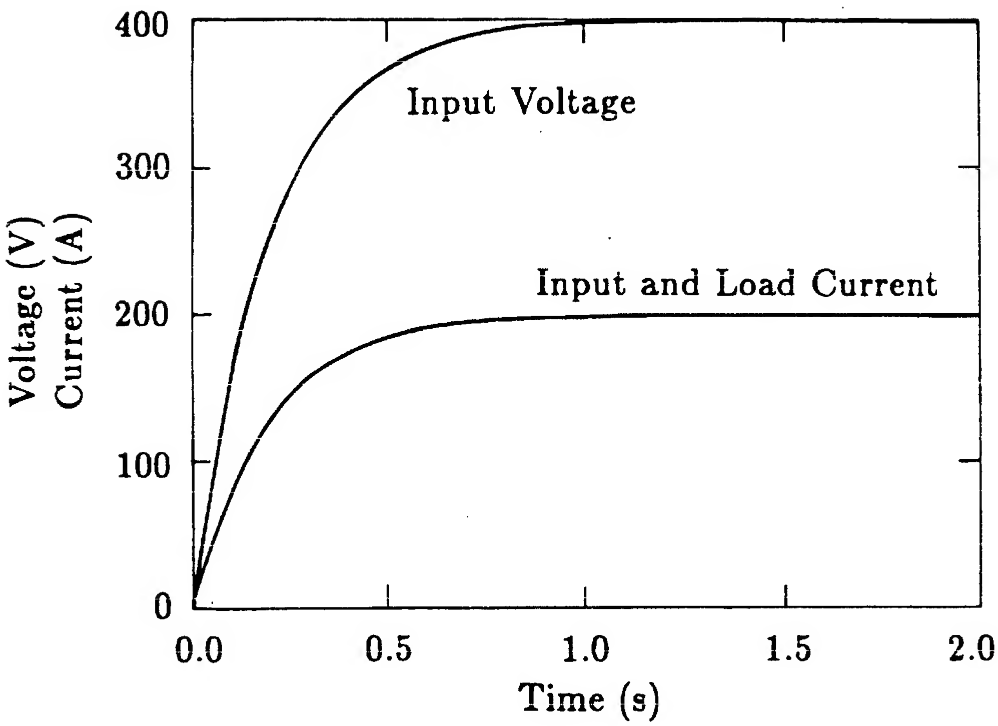
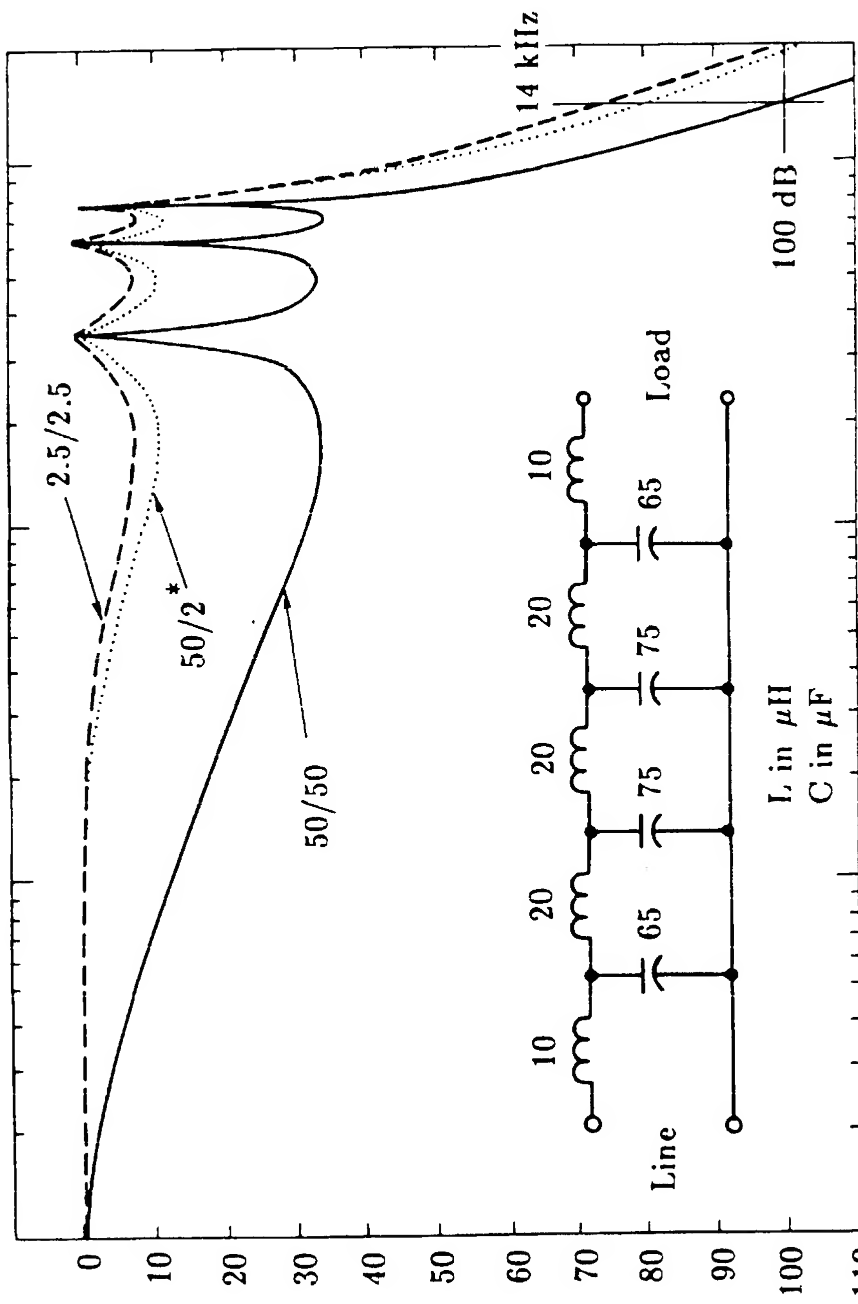


FIGURE 88. Responses of capacitive-input filter to the long pulse ($R_0 = 3\ \Omega$, $R_L = 2\ \Omega$).

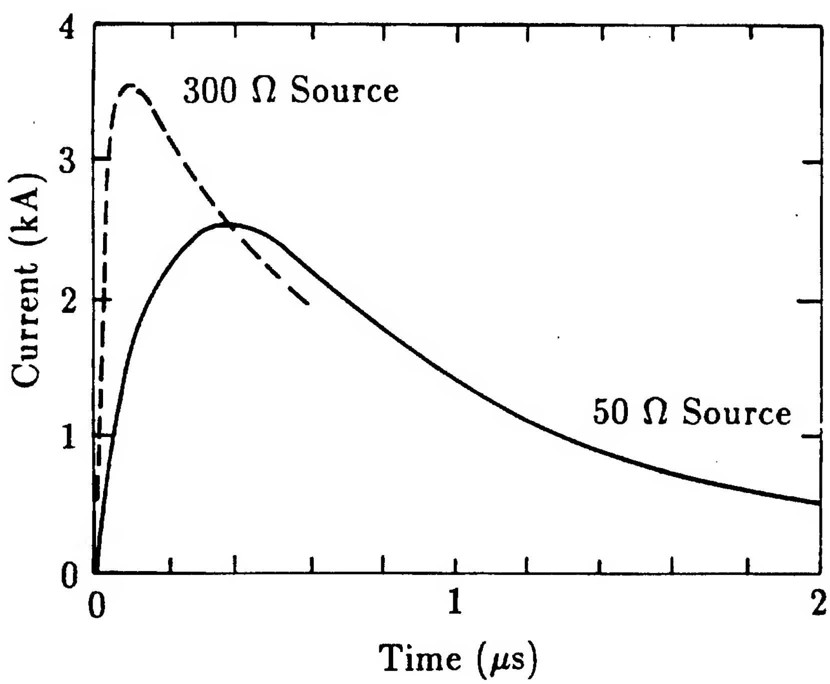


* 50/2 Denotes $R_o = 50\Omega$ and $R_L = 2\Omega$

FIGURE 89. Insertion loss of inductive-input filter for various (source/load) impedances.

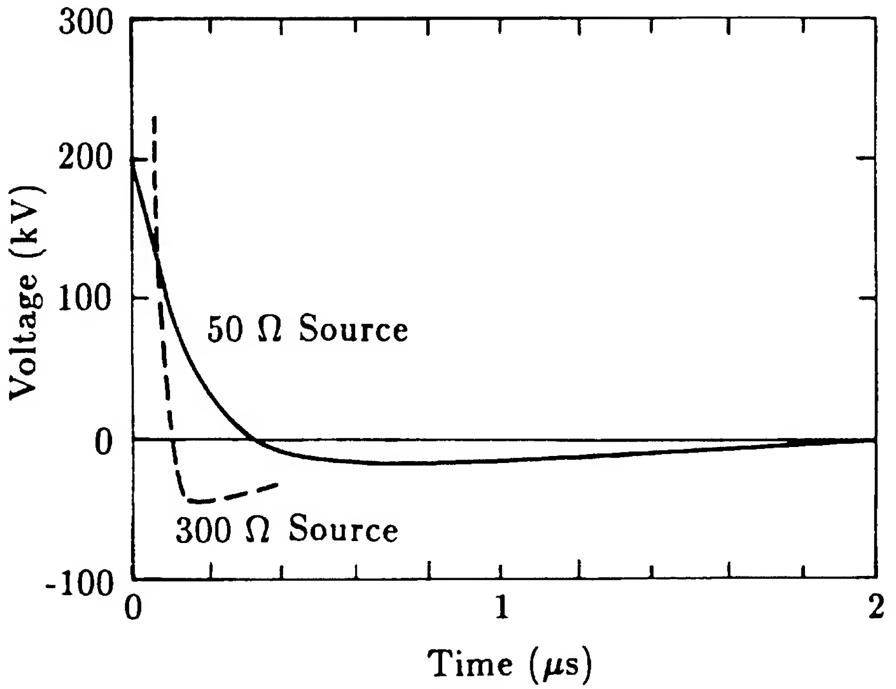
12.1.3.5.1 Short pulse response. The inductive-input filter responses to a short pulse are shown in figure 90. The peak voltage across the input terminals is 200 kV, with all but about 50 V across the 10 μH input inductance. The peak current is only 2.4 kA since the inductance limits the current. The current delivered to a 2 Ω load across the output terminals is also shown. This peak current is 16 A, which is 6 A greater than that allowed by MIL-STD-188-125.

Not only is sufficient voltage developed to activate a surge arrester, the survival of the filter may depend on the surge arrester to limit the input voltage to a level that the filter input inductance can tolerate. That is, without a surge arrester, the hundreds of kV developed by the short pulse will likely cause arcing inside the filter. Thus, failure of the surge arrester may lead to failure of the inductive-input filter; failure of the surge arrester

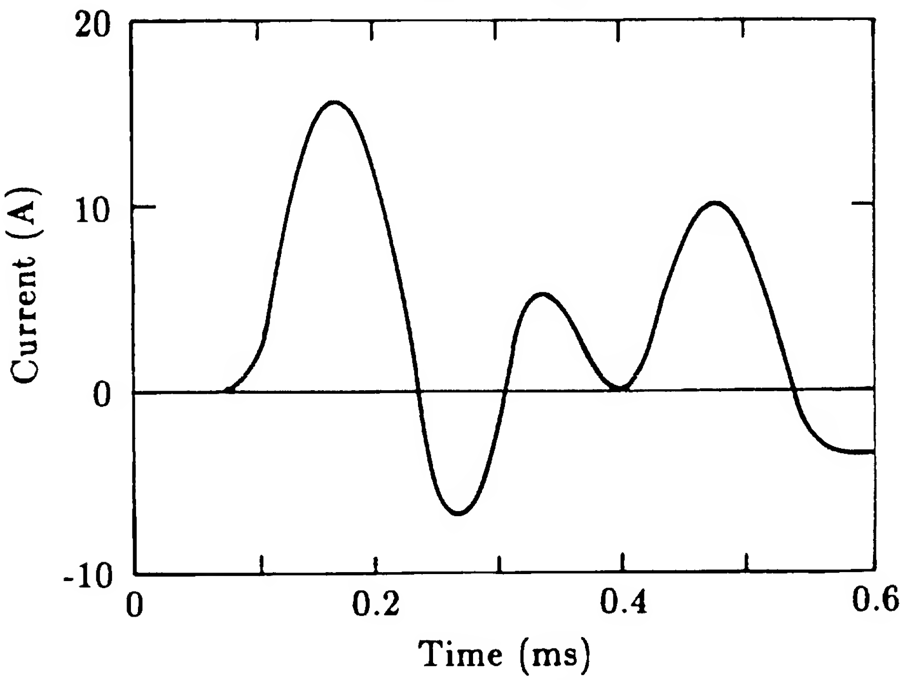


a. Input current I_i.

FIGURE 90. Responses of an inductive-input filter to a short pulse for 50 Ω and 300 Ω source impedance and 2 Ω load.



b. Input vo'tage V_i.



c. Load current I_L.

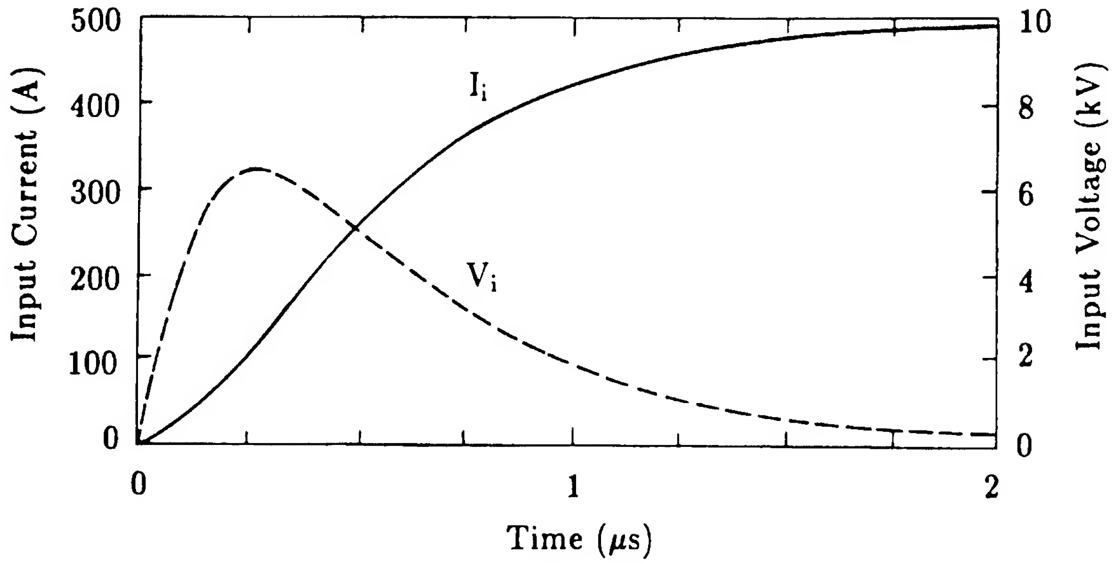
FIGURE 90. Responses of an inductive-input filter to a short pulse for 50 Ω and 300 Ω source impedance and 2 Ω load (continued).

on a capacitive-input filter causes the residual transient to slightly exceed that allowed by the standard, because the input capacitance can absorb the short pulse impulse without problem. It is for these reasons that caution is required in the use of the inductive-input filter for HEMP protection.

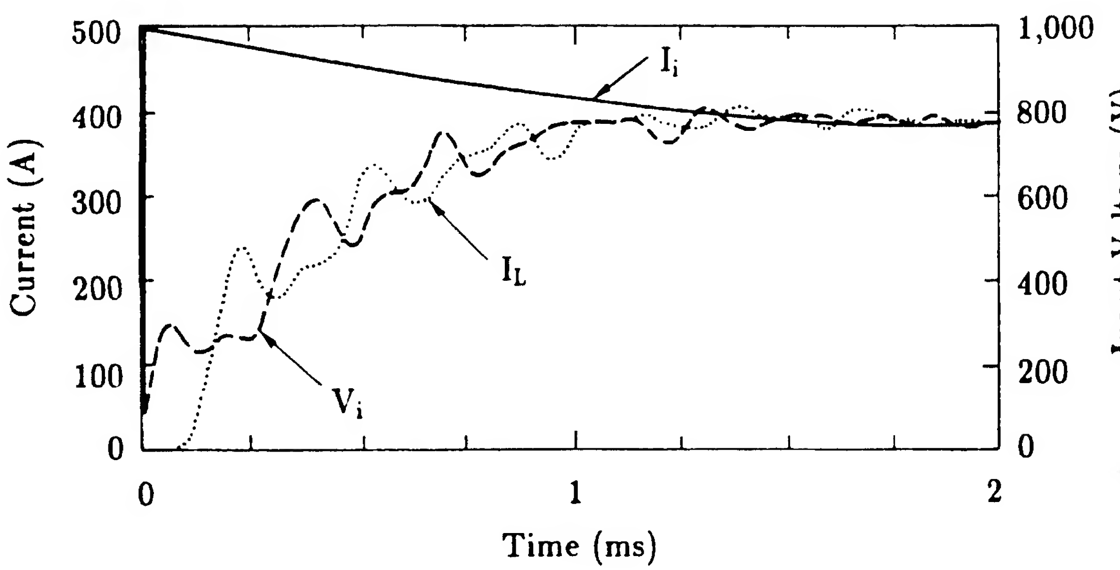
12.1.3.5.2 Intermediate and long pulse. The response of the inductive-input filter to the intermediate pulse is quite similar to the response of the capacitive-input filter, except for a "spike" on the input voltage. The calculated responses are shown in figure 91. The peak voltage across the filter input terminals is greater than 6 kV during the first microsecond, then decays almost to zero as the current through the input inductance builds up. This early voltage is almost entirely across the input inductance, since the first capacitor has accumulated very little charge during the first few microseconds.

During the first 2 ms, the input voltage again builds up to about 800 V. This voltage is almost entirely across the shunt capacitors and 2 Ω load. After 2 ms, there is very little difference between the input and load current, and the input voltage is nominally the voltage across the 2 Ω load. On the leading edge of the input voltage and output current waveforms, an oscillation that is presumably produced by the underdamped inductor-capacitor circuits in the filter occurs. The voltages developed across the input terminals of the filter are sufficient to produce some surge arrester action in fast spark gaps and MOVs. The response of the inductive-input filter to the long-pulse is identical to that of the capacitive input filter in 12.1.3.4.3. The filter is transparent to the long pulse.

12.1.3.6 Effect of source and load impedances. Filter attenuation characteristics are usually measured in accordance with the insertion loss requirements of MIL-STD-220. These tests require that the source and load impedances be controlled during the test at 50 Ω . In actual use in a system, however, the source and load impedances may not be controlled and may vary through these frequencies over a wide range from a few ohms to thousands of ohms, changing alternately from inductive to capacitive reactance. As a result, the insertion loss characteristics measured by the MIL-STD-22O method cannot be relied upon as a true indication of the attenuation to be achieved for HEMP, as has been noted in 12.1.3.4 and 12.1.3.5 for power filters. In addition, the magnetic cores in the filter inductors will saturate under load, if underdesigned, to the extent that the actual filter insertion loss under load may be considerably less than that claimed by the manufacturer. To overcome the fact that filter manufacturers design and build filters in accordance with a military standard that is not a realistic representation of actual filter use, the facility designer must be careful to adequately specify a filter and to require appropriate tests to close some loopholes left open by the use of MIL-STD-22O.



a. Early time.



b. Late time.

FIGURE 91. Responses of an inductive-input filter to the intermediate pulse for 50 Ω source impedance and 2 Ω load.

12.1.3.7 Filter design information. If the designer is involved in specifying the design of a filter, it is recommended that filters contain at least three elements and preferably more. Two-element filters are not very tolerant of impedance mismatches on the input or output. Three-element, pi-section filters have been demonstrated to be relatively tolerant of mismatches. T-section filters are undesirable because of the risk of arcing of the input inductor. Multisection filters, such as the Butterworth, are more tolerant of impedance variations and are generally acceptable. The number of elements needed beyond the recommended minimum three-element filter will depend on the total attenuation requirement and how steeply the attenuation must rise in the transition from the low-pass region to the higher attenuation region.

12.1.3.8 Military specifications and standards applicable to filters. Three documents (MIL-F-15733, MIL-STD-220, and MIL-STD-2O2) are often used for the specification of filter performance. This section explains the use of these documents.

MIL-F-15733 (reference 12-19) is a general electrical filter specification. It governs critical design features for all electrical filters, such as:

a. Range of operating temperatures

b. Impregnant flash point

c. Terminal size and strength

d. Dielectric withstanding voltage

e. Voltage drop

f. Insulation resistance

g. Filter sealing means

h. Overload ratings

i. Finish

j. Moisture resistance

k. Filter marking

MIL-STD-220 is the available test standard for the measurement of electrical filter insertion loss. The test methods in this standard are intended to provide data for quality control during quantity production of power filters. The test conditions specified with

50 Ω input and output terminations are satisfactory for this control purpose, but do not represent conditions that exist in actual circuits or installations. The power source and load impedances at actual installations are typically much lower than 50 Ω at frequencies in the pass band and well into the filter's rejection band. In addition, the actual load impedances vary widely, are not constant as a function of frequency, typically have a leading power factor, and are often nonlinear. Section 16 includes recommended factory and in-situ tests to overcome these limitations, and to enhance the chances of obtaining filters that perform properly.

MIL-STD-202 (reference 12-20) provides the details of test methods for many types of tests of electrical components and parts, and it is referenced in MIL-F-15733 for many of the required tests.

12.1.3.9 Packaging constraints. Filters must be installed in enclosures with internal barriers between the input and output. If this is not done, the insertion loss of the filter will be severely limited by crosstalk from input to output leads. Without a barrier, the attenuation may only be 10 dB to 50 dB, regardless of the insertion loss ratings of the filter. Filters will vary in size depending on the load current, the required insertion loss, the number of lines being filtered, and whether the attenuation is to be measured at full-load current.

Thermal characteristics of the filters under load must be considered *in* both the packaging and installation of the packaged filters in the facility. Certain packaging techniques and installation configurations may combine to cause higher than planned operating temperature conditions. These conditions can in turn cause line voltage and phase imbalances that reduce filter life. Simple thermal analyses should be performed to evaluate the thermal stress on the filters.

12.1.4 Power apparatus for isolation. This subsection describes the use of power apparatus, such as transformers, motor-generators, circuit breakers, and fuses, to isolate the electric power circuits in the facility from the HEMP-induced transients on the external power lines. The primary application of the power apparatus described here is to interrupt the long-lasting, HEMP-induced current represented by the long pulse in MIL-STD-188-125. This 200 A peak, 100-s full-width at half maximum amplitude transient may produce damage in internal equipment, unless it is diverted or interrupted. The Thevenin-equivalent source driving this current is a 5 Ω source with a peak open-circuit voltage of 1000 V. The charge and energy transfer represented by the current are 29 kC and 2.9 MJ/ Ω, respectively. Thus it may prove easier to interrupt the current than to divert it, since surge arresters that are actuated by less than 1000 V and will tolerate megajoules or kilocoulombs are not readily available.

Although the long pulse current interruption device must withstand the 1000 V open-circuit voltage associated with the long pulse, it must also tolerate the higher voltages imposed by the short and intermediate pulses. Since these voltages are much larger than that of the long pulse voltage, additional protection (e.g. surge arresters) will be required for the short and intermediate pulses.

12.1.4.1 Transformers. Transformers may be used to provide late-time isolation between the commercial power lines and the facility. The features of transformers that make them attractive for HEMP isolation are:

a. Common-mode rejection

b. dc blocking

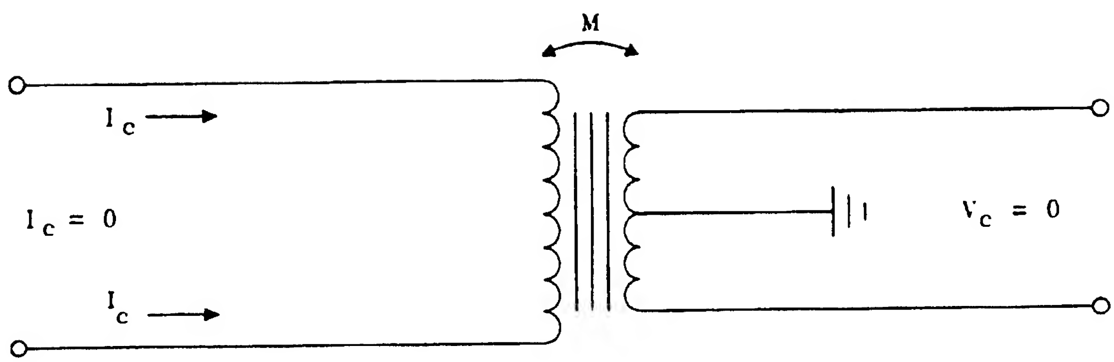
c. High efficiency

d. High reliability

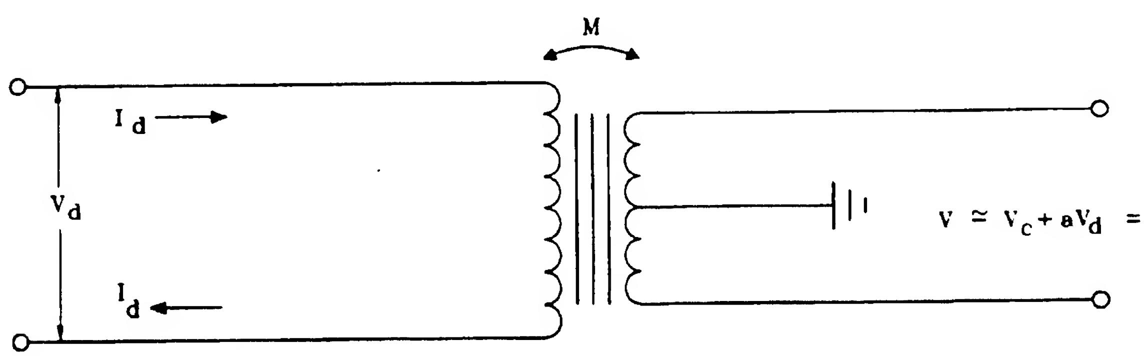
The use of transformers for ac common-mode rejection has long been practiced in the telephone and audio industries. The transformer in figure 92 allows the differential mode signal I_d to be coupled from the primary winding to the secondary winding. The transformer represents an open circuit to an ac source of common-mode interference, however, so that no common-mode current I_c can flow in the primary and no common-mode voltage occurs in the secondary winding. The common-mode rejection of the transformer is most effective at medium frequency (MF) and below. At higher frequencies, the reactance of stray capacitances and inductances may produce imbalance in the impedances of the transformer. This may cause some of the ac common-mode excitation to be converted into differential mode currents. Special care is required to achieve common-mode rejection at HF and above.

If the interfering common-mode signal is dc, the transformer's common-mode rejection will block this. In the differential mode, however, the transformer cannot pass dc currents from primary to secondary windings (figure 93). Thus the transformer may be used to reject dc or very slowly varying interference, such as the long pulse of MIL-STD-188-125, even when the excitation has a differential-mode component. The effects of core saturation by the long pulse must be evaluated for either transformer configuration.

Transformer design is a mature technology; hence transformers are very reliable. In addition, the transformer is one of the most efficient electrical devices. Thus the use of power transformers as HEMP barrier elements should be both economical and relatively maintenance-free.



a. Common mode excitation.



b. Differential mode excitation.

FIGURE 92. Principle of common mode rejection using transformer.

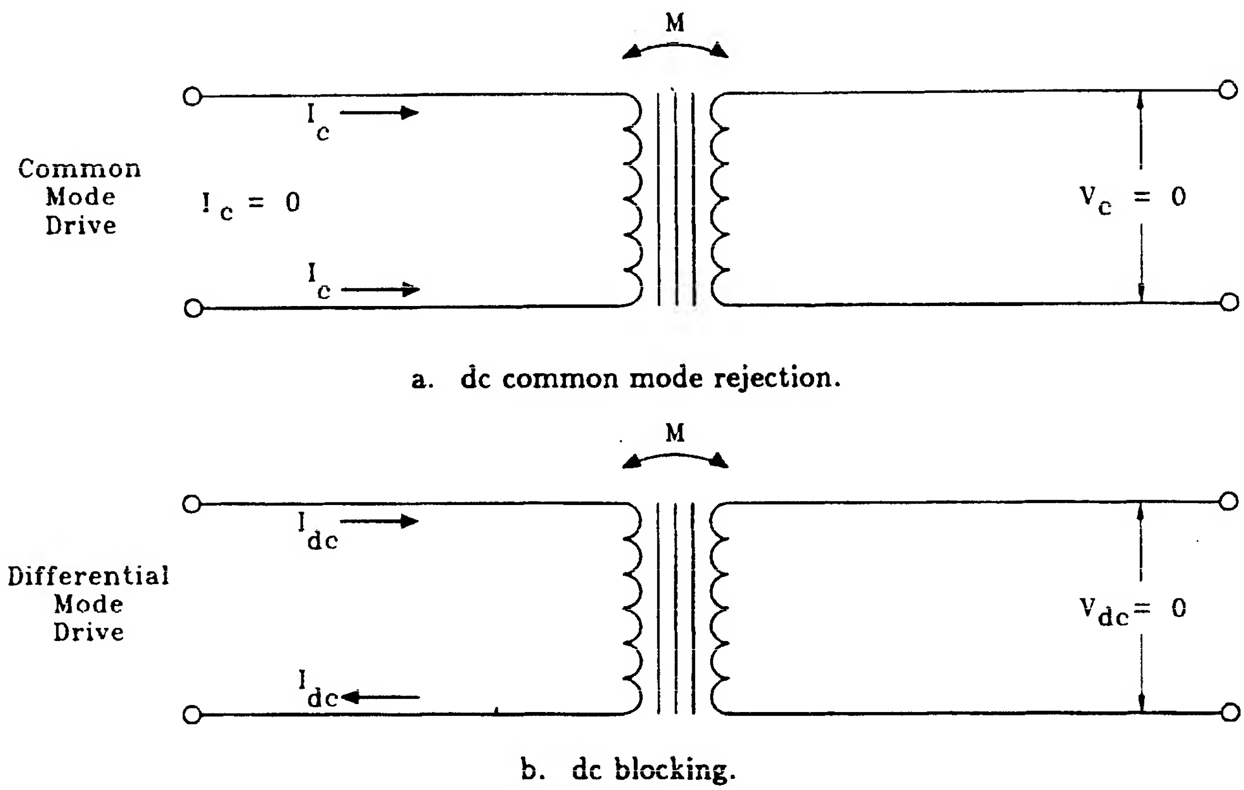


FIGURE 93. Principle of common mode rejection and dc blocking with power transformer.

12.1.4.1.1 Power transformers. Transformers that can be used for 60-Hz power service include the ordinary distribution-type transformer and the shielded isolation transformer. The distribution transformer is almost always installed at or near the facility to reduce the distribution voltage (3 kV or more) to the user voltage (120-480 V). The distribution transformer is often owned and controlled by the electric power company, but arrangements can be made to have it installed in a particular configuration. Alternatively, the facility transformer may be owned and controlled by the facility, if this can be arranged with the local power company. An isolation transformer is usually owned, installed, and controlled by the facility owner, and it is often used primarily for interference control or communication security.

Primary-to-secondary coupling characteristics have been measured on 25 kVA and 50 kVA distribution transformers (reference 12-21). Figure 94 shows the transfer function from a primary common-mode excitation voltage to the secondary common-mode voltage

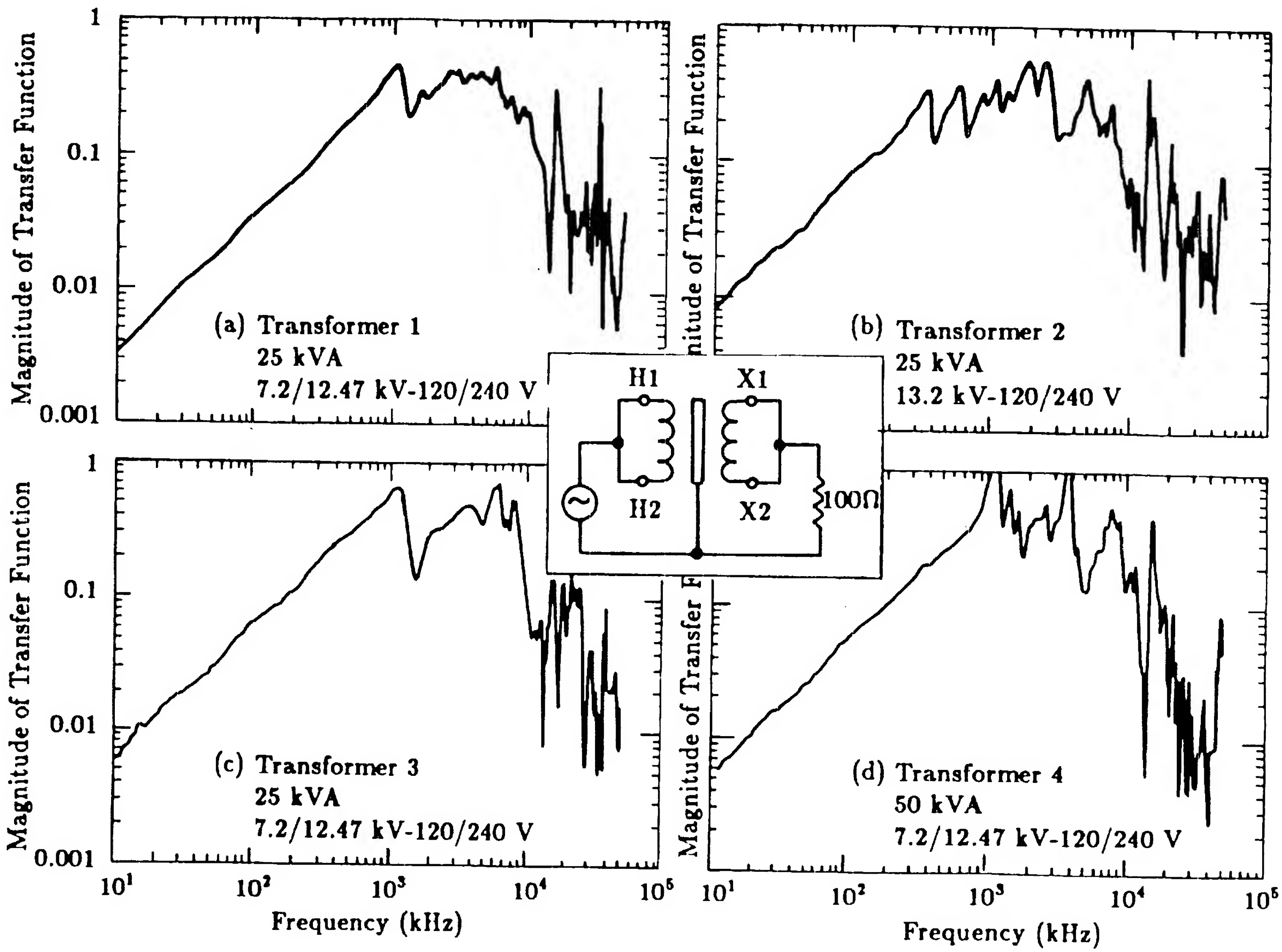


FIGURE 94. **Magnitude of transfer function relating common mode primary voltage to common mode secondary voltage across a 100 Ω load for the test transformers (reference 12-21).**

across a 100 Ω load. Below 1000 kHz, the coupling has the characteristics of a capacitance between the primary and secondary windings. This behavior is fairly typical of unshielded power transformers. This effective coupling capacitance for these transformers is about 1 nF. The basic insulation level of these transformers is 95 kV; that is, the transformer can withstand a 95 kV transient common-mode voltage. The coupling with common mode excitation and a differential mode load is shown in figure 95 for the same four transformers. The coupling is smaller in this mode, but not simply characterized. The differential mode response is due to imbalance in transformer construction and is, perhaps, accentuated by winding resonances. The primary winding is often self-resonant at a frequency of 10 kHz or lower, and the secondary winding may be self-resonant at 100 kHz or higher frequencies.

In the normal operating (differential) mode, the low-frequency (late-time) model of the transformer is given in figure 96, with the secondary terms transferred to the primary side through the turns ratio a. For transformer 4, typical values of the primary copper resistance R_1, the primary leakage reactance X_1, the magnetization reactance X_m, and the core loss resistance R_c are as follows:

$$\begin{aligned} R_1 &\approx 6\,\Omega \approx a^2 R_2 \\ X_1 &\approx 8\,\Omega \approx a^2 X_2 \\ R_c &\approx 270\text{ k}\Omega \\ X_m &\approx 40\text{ k}\Omega = \omega L_m \end{aligned}$$

The de and late-time blocking are due primarily to the fact that X_m shorts the transformer circuit at dc and low frequencies. Since the rated load at 7.2 kV is 1.04 k Ω, the transformer "blocks" frequencies for which $X_m \leq 1.04$ k Ω or $f \leq 1.6$ Hz.

12.1.4.1.2 Isolation transformers. Commercially available isolation transformers typically have shielded windings to reduce the effective capacitance between primary and secondary windings. These are usually designed for user voltages of 120/240/480 V and are typically 1:1 (a = 1) transformers. Because of the electrostatic shielding, the common-mode isolation is much better than that of the unshielded distribution transformer at low frequencies. On the other hand, because the isolation transformer is usually wound for user voltages (120-480 V), there are fewer turns than in the primary winding of a distribution transformer. The winding inductance $L_m = X_m/w$ is thus small and, in the differential mode, the coupling between primary and secondary is efficient up to 100 kHz or higher. Thus the shielded isolation transformer may not provide as much differential mode isolation above the lower frequencies as the distribution transformer.

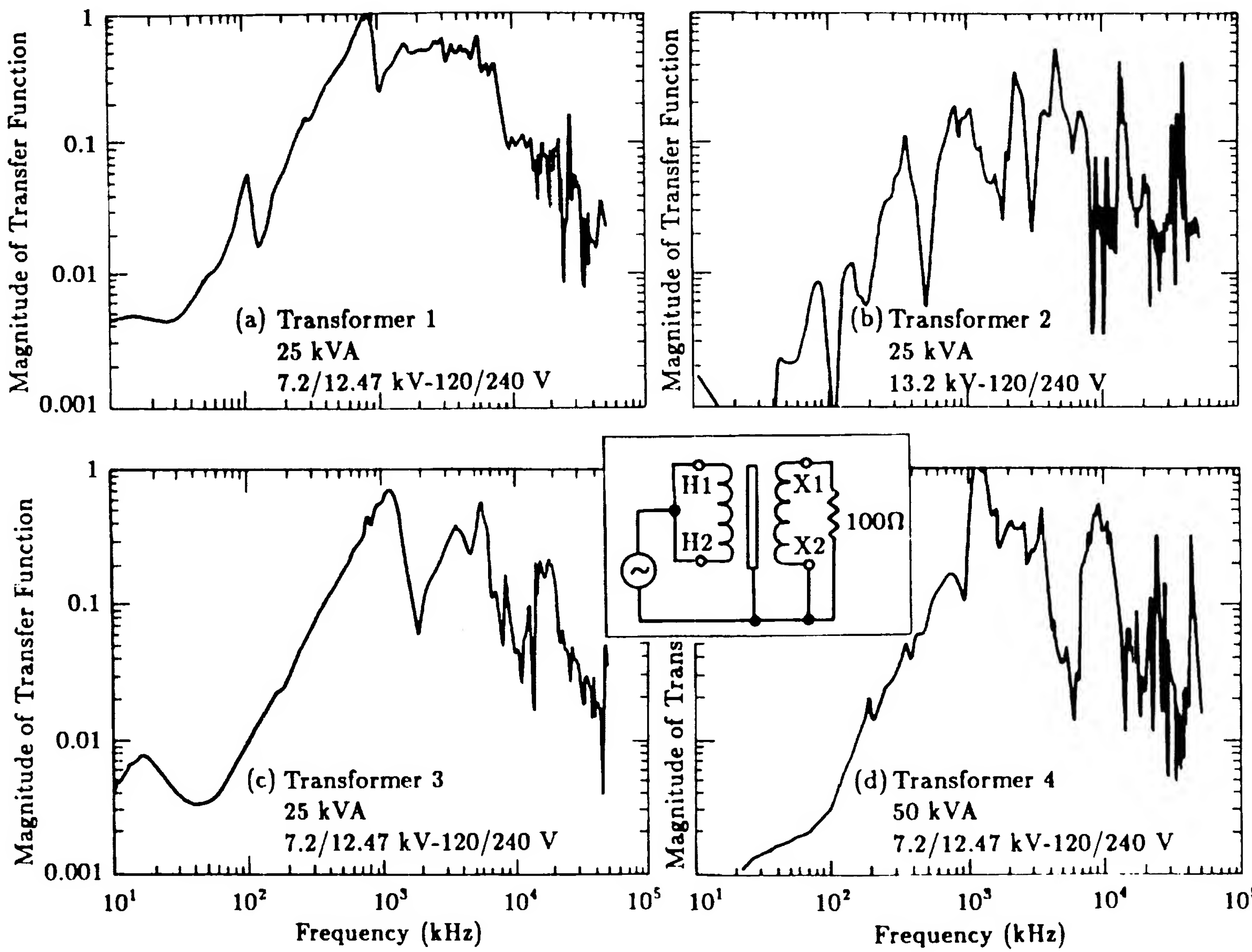


FIGURE 95. **Magnitude of transfer function relating common mode primary voltage to differential mode secondary voltage across a 100 Ω load for the test transformers (reference 12-21).**

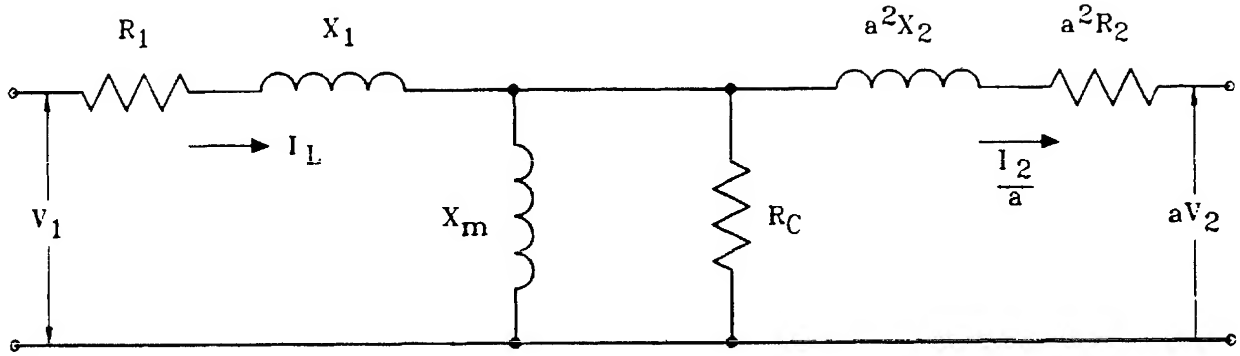


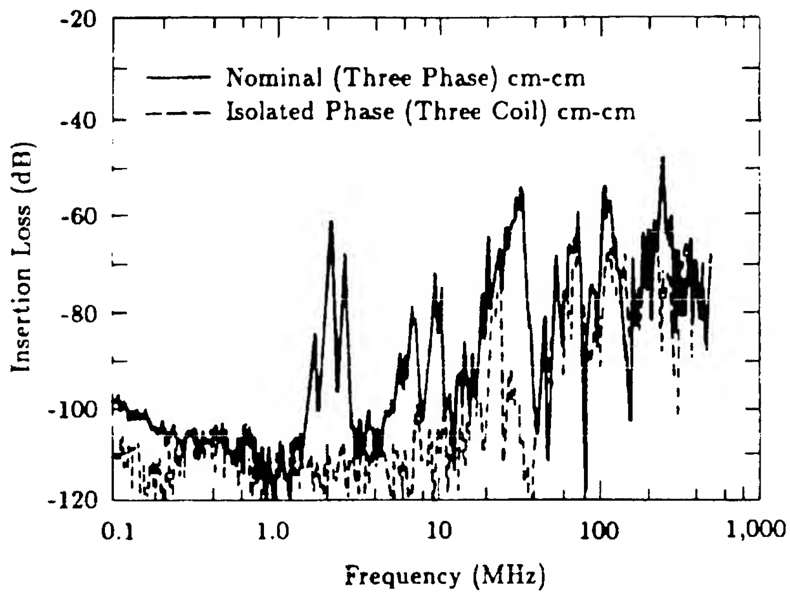
FIGURE 96. Low-frequency equivalent circuit of a power transformer.

A new family of isolation transformers with electrodynamics shields is under development. The electrodynamics shield provides better common mode isolation at high frequencies, so that the isolation transformer can provide the isolation features of the power line filter, but with greater reliability. The insertion loss of a prototype 500 kVA, 480 V, delta-wye shielded isolation transformer is shown in figure 97. The insertion loss is measured in a 50 Ω /50 Ω circuit similar to that specified in MIL-STD-220 for filter tests.

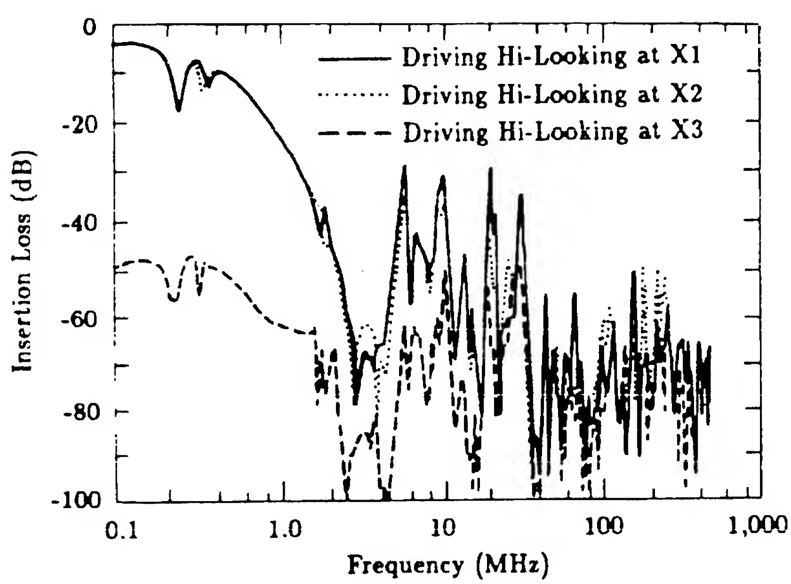
12.1.4.2 Motor-generators. A motor-generator set can be used to eliminate the electrical POE for a power line and replace it with one or more mechanical penetrations. The external source (for a commercial feeder into the facility) or internal source (supplying power to mission-essential equipment outside the electromagnetic barrier) drives the motor, which is the prime mover for the generator or alternator on the opposite side of the facility HEMP shield. At least conceptually, power may be transported across the barrier either through mechanical linkage or with hydraulics.

For the more conventional mechanically linked system, a dielectric shaft penetrating the barrier through a waveguide-below-cutoff can be used to transmit shaft power from the motor to the generator. Waveguide dimensions and construction must satisfy the same requirements specified for a fiber penetration in MIL-STD-188-125. The dielectric shaft configuration is illustrated schematically in figure 98.

Electrical motor-generators with metallic shafts are commercially available from a variety of suppliers in sizes to approximately 100 kW. Including controls (circuit breakers, starters, voltage regulators, monitoring instruments, etc.) which are tailored to needs of the customer, costs for high-power systems are of the order of $100-200 per kilowatt. Conversion to a dielectric shaft presents no significant technical problem, but care in



a. Common mode.



b. Differential mode.

FIGURE 97. Insertion loss of 500 kVA delta-wye shielded isolation transformer.

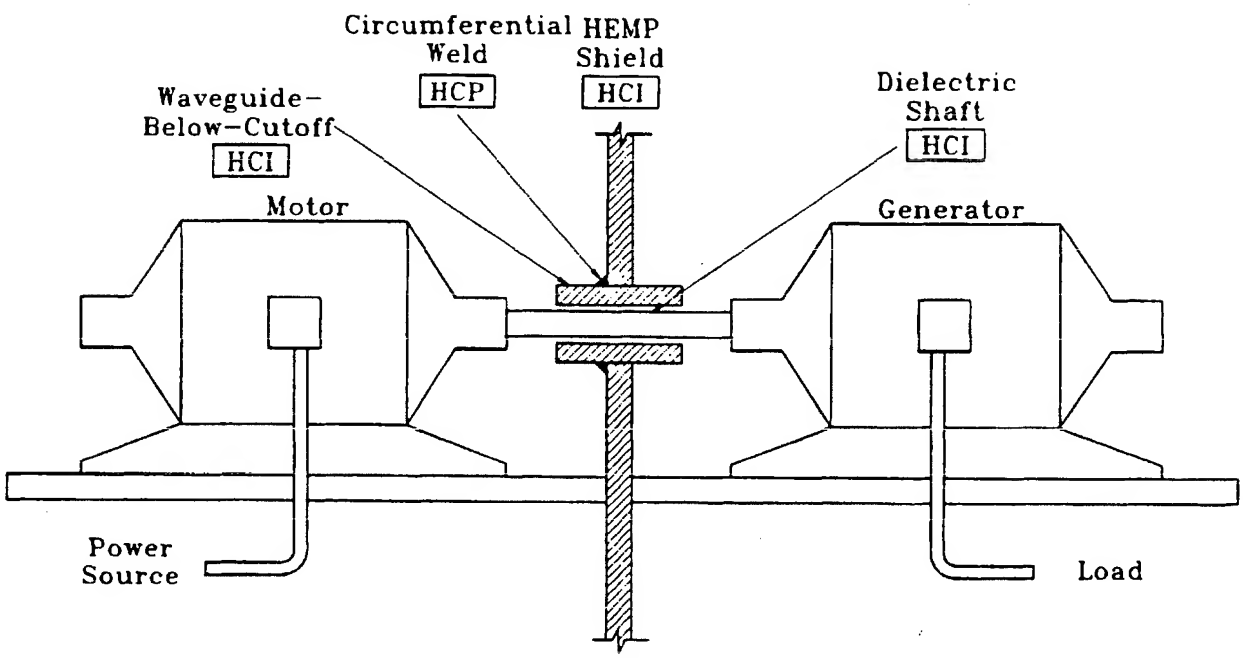


FIGURE 98. Motor-generator used to eliminate electric power penetration.

preserving the alignment is required when the motor and generator will not share a common mounting frame. This concept's use is limited in size to facilities requiring 50 kW or less.

A hydraulic system concept is shown in figure 99. The supply and return fluid piping penetrations must be implemented in accordance with requirements of MIL-STD-188-125 (or the machinery metal casing integrated into the shield). Electrical motors/hydraulic pumps and hydraulic motors in appropriate sizes are commercially available. While the combination of the hydraulic motors and generators in appropriate sizes is commercially feasible, vendors offering such assemblies as standard products have not been found. Consequently, no supportable cost estimate can be provided.

The rotational inertia of a motor-generator, with or without a supplementary flywheel, is also effective for suppressing effects of momentary power interruptions or surges. Thus, in areas where momentary outages are frequent, a motor-generator can improve power continuity. It does not present the large leading reactive load which is sometimes an undesirable characteristic of nonpower-factor-compensated filter/surge arrester devices. The third advantage of the approach is improved HEMP protection subsystem reliability, since the associated mechanical penetrations are less vulnerable to isolation performance degradation or failure than electrical POE protective components.

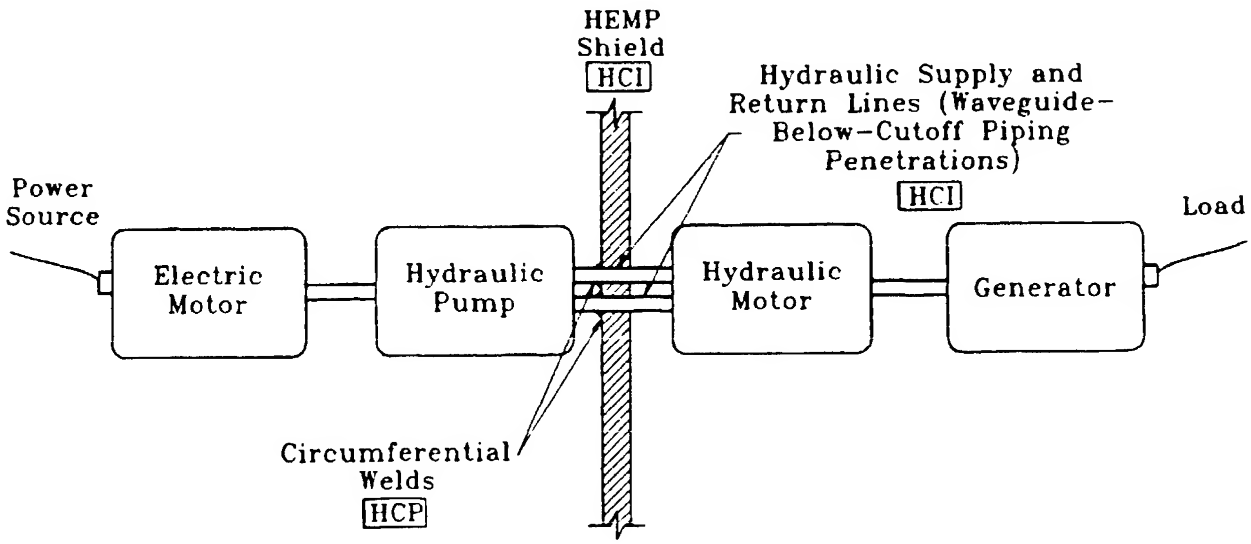


FIGURE 99. Hydraulic motor-generator set.

Disadvantages of the motor-generator concept compared to the filter/ESA include the following:

a. Physical size and initial installation costs are larger.

b. Electrical efficiency of a motor-generator is somewhat less than that of a filter/ESA; thus, operating costs may be slightly higher.

c. Because of bearing wear in large rotating machines, maintenance costs are also likely to be higher for a motor-generator.

Considering all factors, energy supply through a motor-generator is recommended only when there are reasons other than HEMP protection for needing such equipment. However, if such a system is required for power stability or other purposes, use of these concepts for HEMP hardening should be considered.

12.1.4.3 Contactors, circuit breakers, and fuses. Contractors, circuit breakers, or fuses may be used to interrupt power circuits to prevent system damage from the long pulse of MIL-STD-188-125. To be useful, these devices must act quickly when the HEMP-induced late-time current appears, but must not respond to routine transients and current fluctuations. Response times of one second or less are desired to limit the stress on equipment in the facility. In addition, the power circuits must be opened under a 1000 V drive

and withstand the 1000 V across the open-circuit. The applications for these protection devices in typical C[4]I facilities are rather limited.

12.1.4.3.1 Fuses. Fuses generally operate much too slowly to be useful for HEMP protection. Several hundred percent of the rated current is required for a fuse to open the circuit in times of the order of one second (figure 100). Since the long pulse delivers only 200 A into a short circuit, it is not possible for this current to be several times the facility current at facilities with operating currents of several hundred amperes. There may be some small loads where fuses can be used for HEMP protection. For example, an external circuit that is driven indirectly by the long pulse and is not required for essential operations may be protected with a fuse.

12.1.4.3.2 Circuit breakers. Circuit breakers actuated by heat (thermal breakers) are even slower than fuses; hence they require greater overloads to open the protected circuit within one second (see figure 100). For the desired interruption speed, fast-acting

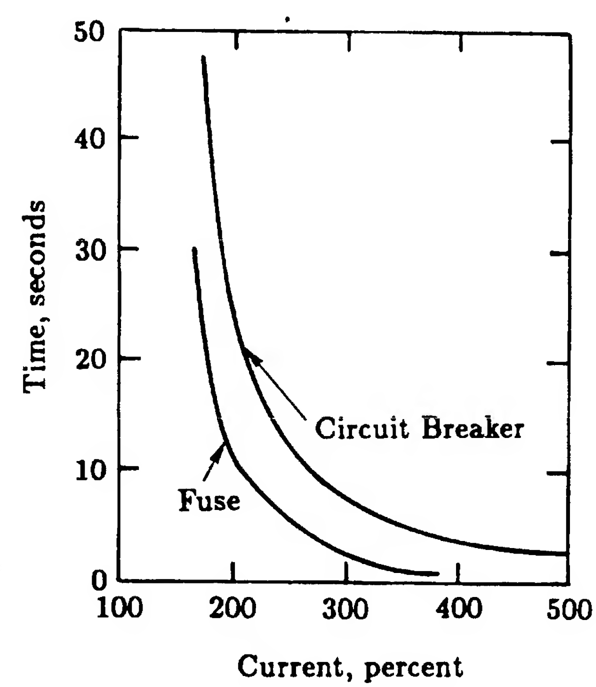


FIGURE 100. Typical time-current curves for a 30-A fuse and a 30-A circuit breaker.

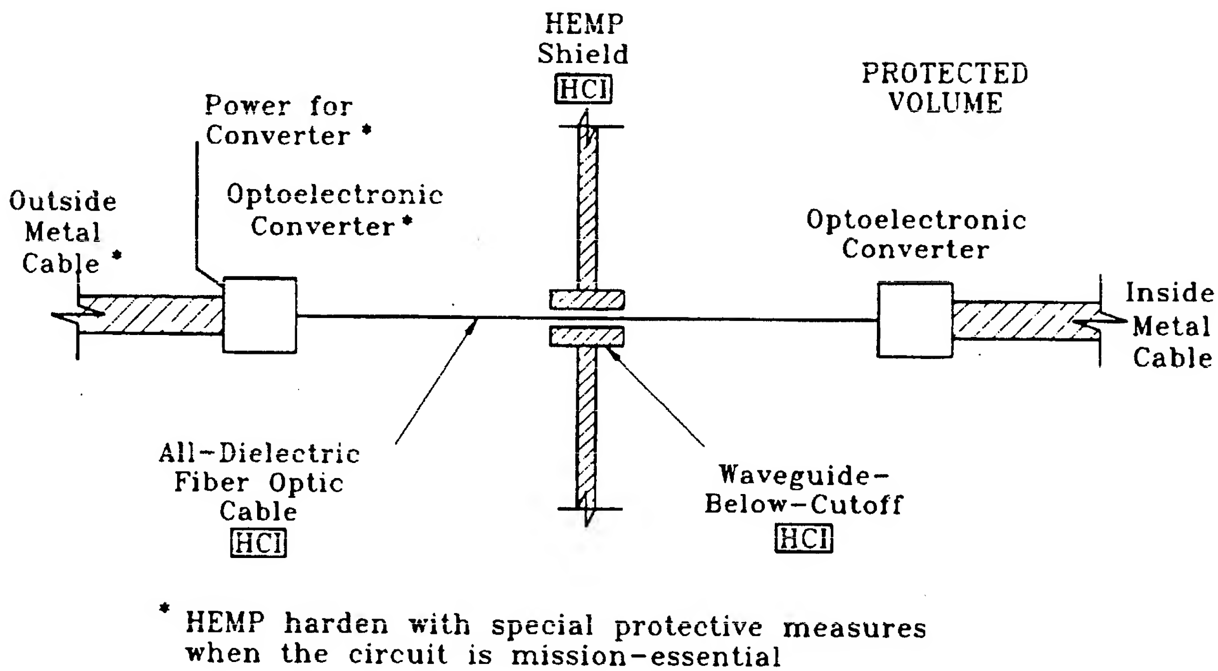
or high-speed circuit breakers are necessary. These are electromagnetically actuated and can clear circuits within a fraction of a second. However, a clear distinction is required between the operating load and the overload that is to be cleared. For many facilities, the 200 A long pulse is not a sufficient overload on the normal 60-Hz operating current to reliably trip the circuit breaker. Conversely, if the circuit breaker is set to trip reliably on the 200 A long pulse, it may also trip frequently on small surges that occur fairly routinely. Thus the high speed circuit breaker is recommended only for low-power facilities (< 100 A).

12.1.4.3.3 Contractors. Contractors that are actuated by a HEMP sensing circuit have also been developed to interrupt the power circuit on the detection of simulated HEMP. Systems that reliably sense the nuclear HEMP are probably too expensive to consider solely for the purpose of power line protection. However, facilities which have access to reliable HEMP detectors could use the information from the detectors as a part of the facility power protection scheme. Sensing systems have also been developed and tested with a single simulated HEMP waveform. However, the HEMP of nuclear detonations may be radically different from the test simulation and may not necessarily trigger the sensing system.

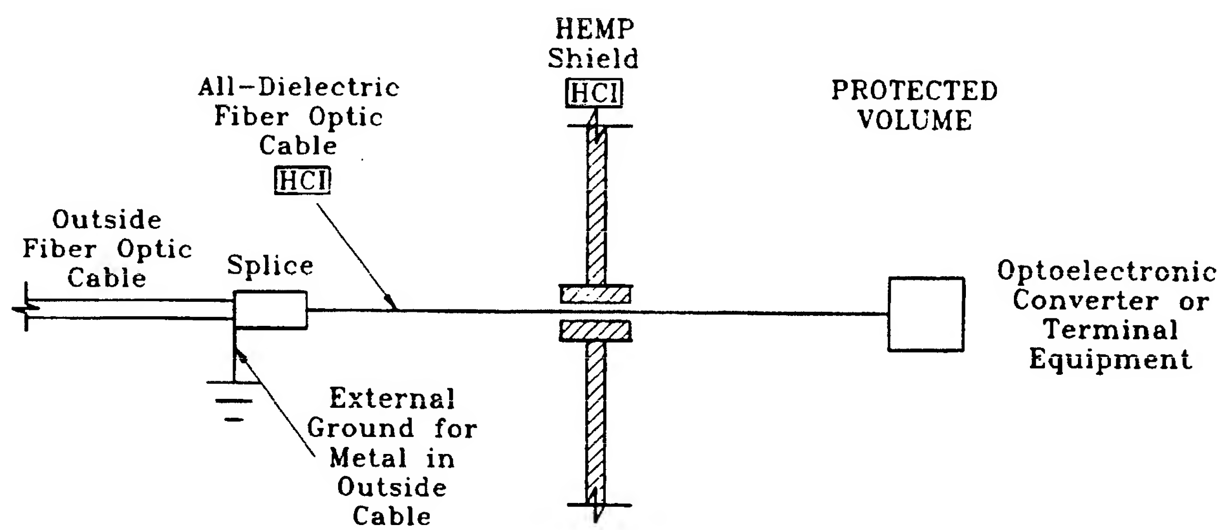
12.1.5 Optical isolation devices. MIL-STD-188-125 requires that all standard voice and data lines be converted to fiber optics outside the HEMP barrier and that all-dielectric fiber optic cables be used to penetrate the shield. To accommodate this requirement when the external cable is metallic, an optoelectronic conversion must be made outside the shield as illustrated in figure 101a. If the circuit is mission-essential, this converter must be hardened with special protective measures. The optical signals are then transmitted through the shield on an all-dielectric fiber optic cable and, as needed, they are reconverted to electrical signals inside the barrier.

When the external line is a metal-reinforced optical cable, it is necessary to splice to an all-dielectric cable before penetrating the shield as shown in figure 101b. The optoelectronic conversion techniques and optical fiber cable characteristics are discussed in this subsection.

12.1.5.1 Fiber optic cable. Optical fiber cable for long-haul telecommunications usually has metal strength members and metallic rodent shields, and it often contains twisted pairs for use by installation and maintenance crews. Almost all outside cable in the U.S. has one or more of these metal members. All-dielectric cable is available, however, and a few operating companies have used all-dielectric cable in their outside cable installations. All-dielectric cable is required for penetrating the HEMP shield, since metal armor, tension members, or other wires would convert the waveguide-below-cutoff into a coaxial geometry. It is important to specify all-dielectric cable for the fiber optic



a. Outside metal cable.



b. Outside fiber optic cable.

FIGURE 101. Fiber optic conversion and shield protection.

link penetrating the shield. Fiber optic cable used in the outdoor environment should also be clad in a nonconductive sheath that resists abrasion and ultraviolet radiation.

12.1.5.2 Optoelectronic converters. The exterior optoelectronic converter transforms the electrical signal received on metal pairs to an optical signal that is launched onto an optical fiber. The process may also include multiplexing to combine several electrical signals into one optical signal. The conversion may be performed with light-emitting diodes (LEDs) or laser diodes (reference 12-22).

Light-emitting diodes are generally more limited in range and data rate than the laser diodes. Ranges from a few meters to a few kilometers can be achieved with LEDs, at bit rates of 5 to 200 Mbit/s. LED converters are thus adequate for converting audio/data signals to optical signals for fiber optic penetration of the shields.

The laser diodes have more spectral purity, narrower emitted light beam width, and greater efficiency in producing light signal from electrical signal. Thus, laser diodes are better suited to long distance transmission. Laser diodes can transmit over tens of kilometers at bit rates of up to 1000 Mbit/s.

Electrical-to-light signal converters are available in a variety of sizes and capacities, ranging from single channel units to multichannel systems with their own power supplies and multiplexer. Converters for mission-essential cables outside the facility shield must be protected against HEMP and must be provided with protected operating power. Protection of the converters is discussed in 12.3.3.

The optoelectronic converters that transform the received optical signal from the optical fiber light guide into an electrical signal will be located inside the facility. For an isolation link such as that illustrated schematically in figure 101a, this converter must restore the electrical signal to essentially the same form as the signal entering the exterior converter. The interior converter also requires an operating power source but, since it is inside the facility shield, it can be operated from the facility HEMP-hardened electrical power and distribution system.

The critical element of the light-to-electrical converter is a photodiode. Two types of photodiodes are commonly used: the PIN diode and the avalanche photodiode. The PIN diode is less sensitive and more limited in data rate than the avalanche photodiode, but quite adequate for many isolation link applications. Figure 102 shows a comparison of the sensitivity and bit rate for these devices for a bit error rate of 10^{-9} (reference 12–22).

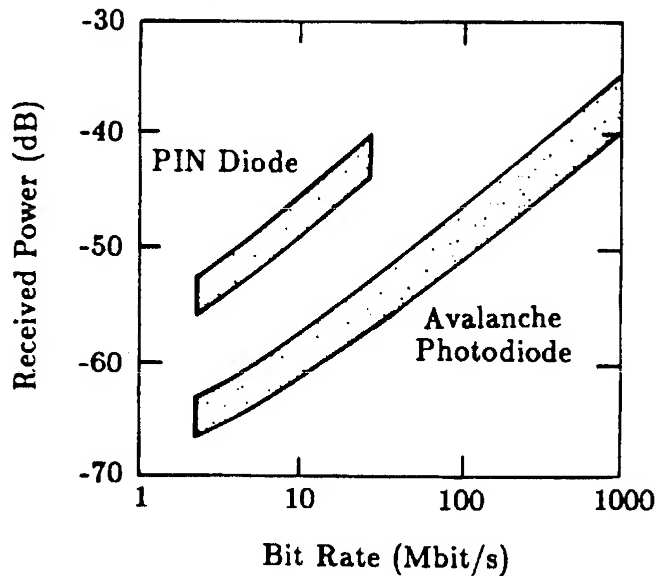


FIGURE 102. Sensitivity of a PIN photodiode and an avalanche photodiode (reference 12–22).

12.1.5.3 Reliability. Because the fiber optic link involves the addition of active electronics for both conversions, the reliability of the audio/data transmission system may be affected by the addition of the fiber optic link. However, the effect on reliability should be minor, if standard telecommunication-quality equipment is used for the fiber optic link. This is contingent on protection of the power supply, cables, conduits, and the fiber optic cables against pedestrian and vehicular damage, weather, and other environmental damage.

If the fiber optic link merely serves as an interface between metal-reinforced outside fiber optic cable and all-dielectric cable as illustrated in figure 101b, the effect on reliability should be negligible. This assessment is contingent on standard telecommunications practices being used in installing the all-dielectric section and in protecting the splice from physical and environment degradation.

12.2 MIL-STD-188-125 general requirements for electrical POEs.

5.1.7 Electrical points-of-entry.

5.1.7.1 HEMP protection for electrical POEs. HEMP protection for electrical POEs, including all power, communications and control penetrating conductors whether shielded or unshielded, shall be provided with transient suppression/attenuation devices (except under conditions identified in 5.1.7.9).

5.1.7.1.1 Electrical POE protective device requirements. A transient suppression/attenuation device shall consist of an electrical surge arrester and additional linear and nonlinear elements as required. The varistor voltage at 1 mA direct current d.c. (for a metal oxide varistor) or the d.c. breakdown voltage (for a spark gap) shall be 150 to 250 percent of the peak operating voltage on the line. The protective device shall limit the residual internal transient stress to a maximum prescribed for each class of electrical POE, when prescribed pulses are injected at its external terminal (see table I). Additionally, the protective device shall be rated to withstand at least 2000 short pulses at the prescribed peak injection current without damage or performance degradation, as defined in test procedures of appendix B.

5.1.7.1.2 Electrical POE protective device installation. Electrical POE protective devices shall be installed in the configuration shown in figure 5. The external and internal conduits and compartment covers do not have shielding requirements as part of the electromagnetic barrier, but shielding may be necessary as a special protective measure (see 5.1.8) or to satisfy other electromagnetic requirements. The presence of the protected electrical POE shall not degrade shielding effectiveness of the facility HEMP shield below minimum requirements of figure 1.

5.1.7.2 Quality assurance for electrical POE protective devices. AU welded and brazed seams and joints required for installation of electrical POE protective devices shall be monitored under the program of in-progress inspection of welded and brazed seams (see 5.1.3.4.1). Transient suppression/attenuation devices shall be subjected to electrical and mechanical quality assurance tests to demonstrate acceptable performance.

5.1.7.3 Acceptance testing for electrical POE protective devices. Acceptance testing for electrical POE protective devices shall be conducted using the pulsed current injection test procedures of appendix B.

TABLE I. Residual internal stress limits and injected pulse characteristics for classes of electrical POEs.[1]

a. Double exponential waveform injections.

Class of Electrical POE	Residual Internal Stress Limits[1]			Pulsed Current Injection Requirements[1]			
	Type of Measurement	Peak Response Current (A)	Peak Rate of Rise (A/s)	Type of Injection	Peak Injected Current (A)	Risetime (s)	FWHM[1] (s)
Commercial Power Lines (Intersite)							
Short Pulse	Bulk current	10	1×10^6	Common mode	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Short Pulse	Wire current	10	1×10^6	Wire-to-ground	4000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Intermediate Pulse	No damage or performance degradation			Common mode	500	$\le1\times10^{-6}$	$\ge5\times10^{-3}$
Intermediate Pulse	No damage or performance degradation			Wire-to-ground	500	$\le1\times10^{-6}$	$\ge5\times10^{-3}$
Long Pulse	No damage or performance degradation			Common mode	200	≤0.5	≥100
Long Pulse	No damage or performance degradation			Wire-to-ground	200	≤0.5	≥100
Other Power Lines (Intrasite)							
Short Pulse	Bulk current	10	1×10^6	Common mode	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Short Pulse	Wire current	10	1×10^6	Wire-to-ground	4000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Audio/Data Lines (Intersite)							
Short Pulse	Bulk current	0.1	1×10^6	Common mode	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Short Pulse	Wire current	0.1	1×10^6	Wire-to-ground	[3] $8000/\sqrt{N}$ or 500	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Intermediate Pulse	No damage or performance degradation			Common mode	500	$\le1\times10^{-6}$	$\ge5\times10^{-3}$
Intermediate Pulse	No damage or performance degradation			Wire-to-ground	500	$\le1\times10^{-6}$	$\ge5\times10^{-3}$
Long Pulse	No damage or performance degradation			Common mode	200	≤0.5	≥100
Long Pulse	No damage or performance degradation			Wire-to-ground	200	≤0.5	≥100
Control/Signal Lines (Intrasite)							
Short Pulse	Bulk current	[4] 1.0 or 0.1	1×10^6	Common mode	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Short Pulse	Wire current	[4] 1.0 or 0.1	1×10^6	Wire-to-ground	[3] $8000/\sqrt{N}$ or 500	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
RF Antenna Lines–Signal Conductors							
[5] $f \le 2$ MHz	Wire current	[6] 1.0 or 0.1	—	Wire-to-shield	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
RF Antenna Lines–Shields							
Buried[7]	Shield current	0.1	1×10^6	Shield-to-ground	1000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Nonburied	Shield current	0.1	1×10^6	Shield-to-ground	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Conduit Shields							
Buried[7]	Bulk current	[8] 10, 1.0, or 0.1	1×10^6	Conduit-to-ground	1000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}
Nonburied	Bulk current	[8] 10, 1.0, or 0.1	1×10^6	Conduit-to-ground	8000	[2] $\le1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}

TABLE I. *Residual internal stress limits and injected pulse characteristics for classes of electrical POEs (concluded).*

b. *Damped sinusoidal waveform injections.*

Class of Electrical POE	Residual Internal Stress Limits[1]			Pulsed Current Injection Requirements[1]			
	Type of Measurement	Peak Response Current (A)	Peak Rate of Rise (A/s)	Type of Injection	Peak Injected Current (A)	Center Frequency (MHz)	Decay Factor (Dimensionless)
RF Antenna Lines–Signal Conductors							
[5] 2 MHz $< f \leq$ 30 MHz	Wire current	[6] 1.0 or 0.1	—	Wire-to-shield	[2] 2500	[2] 2 ± 10%	[2] 10 ± 3
[5] 30 MHz $< f \leq$ 200 MHz	Wire current	[6] 1.0 or 0.1	—	Wire-to-shield	[2] 900	[2] 30 ± 10%	[2] 10 ± 3
[5] 200 MHz $< f$	Wire current	[6] 1.0 or 0.1	—	Wire-to-shield	[2] 250	[2] 200 ± 10%	[2] 10 ± 3

[1] Additional limits on the residual internal stress, other pass/fail criteria, details of the injected pulse waveforms, and circuit test configuration information are contained in the PCI test procedures of appendix B. FWHM is pulse full width at half maximum amplitude.

[2] These parameters of the injected current pulse are design objectives. Minimum injection requirements are contained in appendix B.

[3] Whichever is larger. *N* is the number of penetrating conductors in the cable.

[4] 1 A is the limit for control/signal lines with a maximum operating voltage ≥90 V. 0.1 A is the limit for control/signal lines with maximum operating voltage <90 V.

[5] f = 150/L MHz, where L is the largest dimension of the associated antenna in meters.

[6] 1 A is the limit for transmit or transceive antenna signal conductors. 0.1 A is the limit for receive-only antenna signal conductors.

[7] An antenna shield is considered buried when it terminates at a buried antenna and less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill. A conduit is considered buried when it connects two protected volumes and less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill.

[8] 10 A is the limit for power lines with a maximum operating current ≥10 A. 1 A is the limit for power lines with maximum operating current between 1 A and 10 A. 0.1 A is the limit for control/signal lines and power lines with maximum operating current ≤1 A.

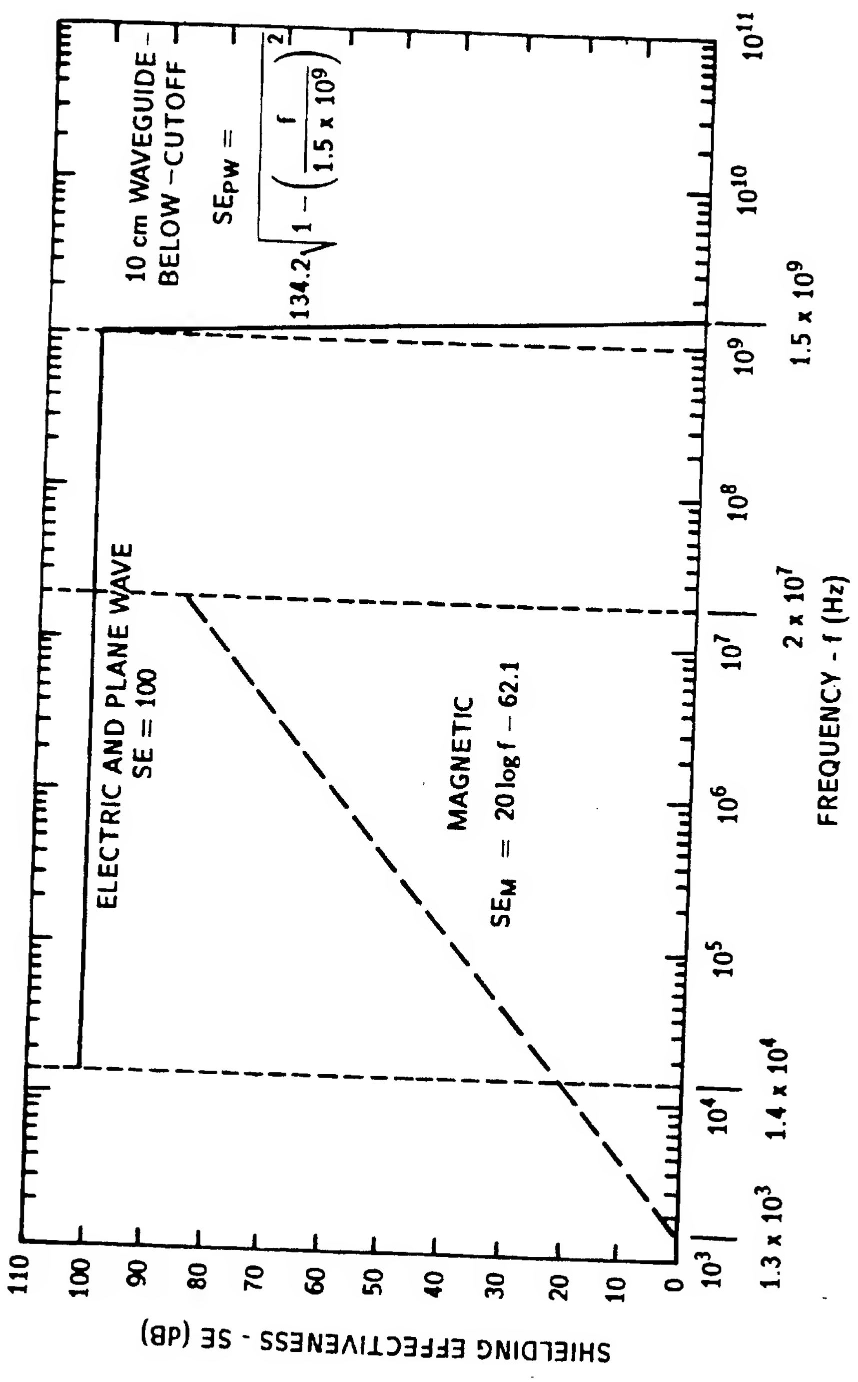
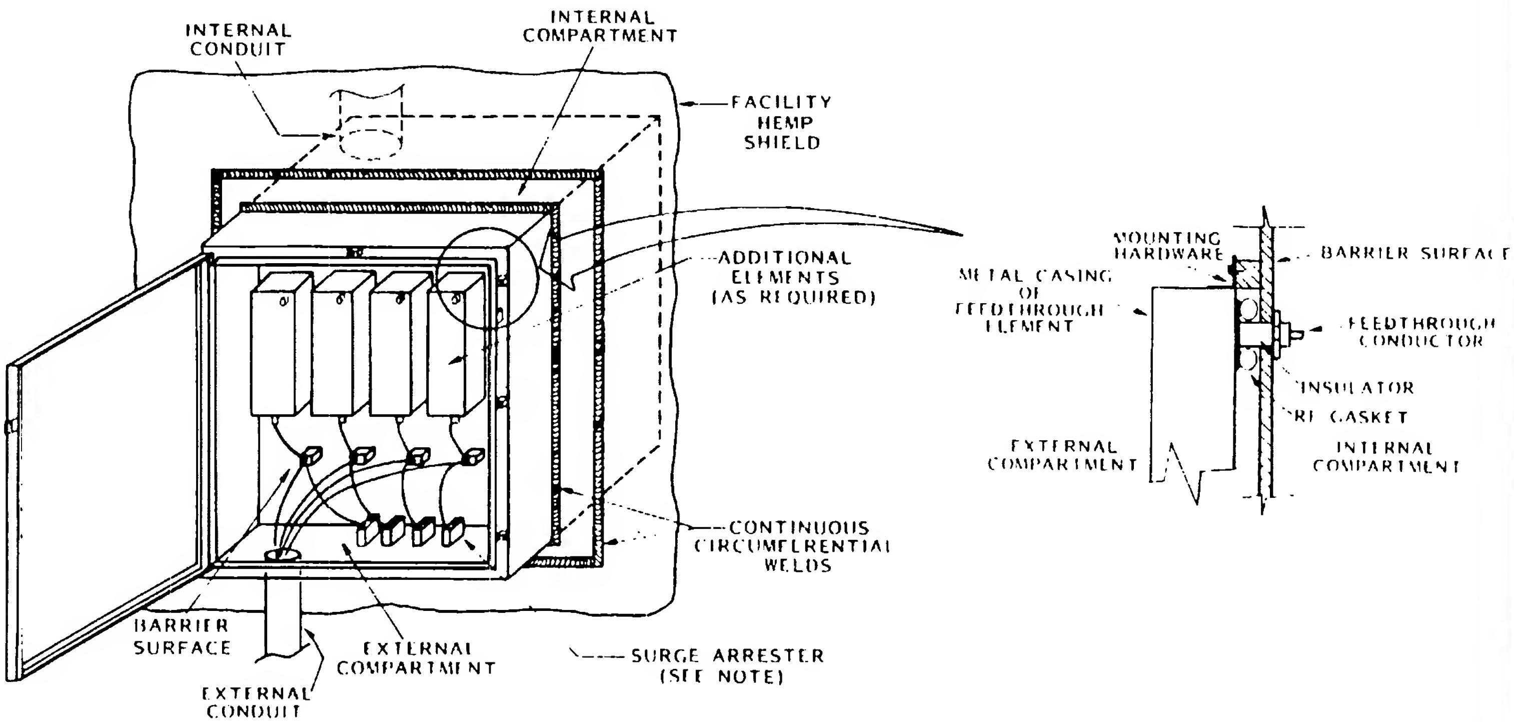


FIGURE 1. *Minimum HEMP shielding effectiveness requirements (measured in accordance with procedures of appendix A).*



NOTE: USE SHORT ELECTRICAL LEADS; CASE OF THE SURGE ARRESTER TO BE GROUNDED TO THE EXTERNAL ENCLOSURE

FIGURE 5. Typical electrical POE protective device.

12.3 Applications.

12.3.1 Treatment of commercial power line POEs.

12.3.1.1 MIL-STD-188-125 requirements for commercial power line POEs. Almost all C^4I facilities are designed to operate from local commercial electric power sources. The utility's distribution lines are usually completely exposed to the HEMP wave, which interacts strongly with the lines. Thus the transients induced by HEMP on the main power feeder lines are severe stresses that must be relieved by transient suppression, attenuation, and interruption. The requirements of MIL-STD-188-125 are:

> 5.1.7.4 Commercial electrical power feeder POEs. Transient suppression/attenuation devices shall be provided on each penetrating conductor of a commercial electrical power feeder POE. The section of the commercial power feeder immediately outside the electromagnetic barrier shall be buried for a length of at least 15.2 m (50 ft). As a design objective, a maximum of two commercial electrical power feeders should penetrate the facility HEMP shield.
>
> 5.1.7.4.1 Commercial power POE protective device requirements. A 4000 A pulse with 10 ns risetime and 500 ns full width at half maximum amplitude (FWHM), occurring on a penetrating conductor at the POE protective device external terminal, shall produce a residual internal transient stress no greater than 10 A and shall not cause device damage or performance degradation.[4] A pulse of 500 A with 1 μs risetime and 5 ms FWHM and a pulse of 200 A with 0.5 s risetime and 100 s FWHM, at the POE protective device external terminal, shall not cause device damage or performance degradation.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals which it is required to pass, a special protective volume shall be established (see 5.1.8.3.2). As a design objective, each commercial power feeder should be provided with a device to disconnect the incoming lines automatically if a HEMP event occurs or manually for alert conditions.
>
> [4] Common mode pulse withstanding requirements, waveform details of the injected pulses, additional constraints on the residual internal transient stress, and circuit test configuration information are contained in PCI test procedures of appendix B.

The acceptance criteria for the intersite commercial power feeders are a residual current limit for the short pulse and a stipulation that no damage or performance degradation shall be caused by any of the three pulses. To satisfy these criteria, it will usually be

necessary to use several barrier elements on the power feeders. MIL-STD-188-125 requires the use of a surge arrester and additional linear and nonlinear elements.

12.3.1.2 Short pulse treatment. The HEMP short pulse induced on a commercial power line can successfully be diverted by conventional filters and surge arresters, since such devices are capable of accommodating the charge transfer and action of this pulse. Power line filters operating at 480/277 Vac and specified to provide minimum insertion loss of 100 dB from 14 kHz to at least 1 GHz (measured in accordance with MIL-STD-220) are readily available in current ratings up to 200 A from a variety of suppliers. A few manufacturers also advertise models with larger current ratings, and most others will provide them as a special order. Compatible MOVs are available from several sources; some filter manufacturers build the ESAs into their assemblies. Past in-service experience with these 480/277 Vac devices has been generally satisfactory.

Experience with HEMP filters at power line voltages in excess of 480/277 Vac has generally been unsatisfactory. Frequent failures have occurred in the past and, in some instances, the events have been explosive. Work is in progress to solve this problem. At the present time, however, acquisition of these higher voltage filters should be handled as a developmental program. To avoid this complication, designers are encouraged to provide the commercial power line entry at 480/277 Vac.

Effects on power factor, harmonic distortion, and transient behavior characteristics of the electrical service installation are other system-level issues that must be considered when selecting the commercial power line filters and ESAs. HEMP power filters achieve their high insertion loss in the rejection band with shunt capacitors and series inductors. The fundamental self-resonant frequency of the reactive filter elements will be in the range of 3–10 kHz. When the operating current on the protected line is small, the filter will be designed with larger inductors and smaller capacitors. At a larger rated current such as that on the main power feeder, reduced inductance and increased capacitance are used to limit the full-load voltage drop.

The commercial power line filter capacitors will draw many tens of amperes of reactive leakage current, with a leading power factor of essentially zero. This leakage may adversely affect the overall facility power factor, particularly if the normal site operating load is a small fraction of the full-load rating. A power source of limited capacity, such as a site backup generator, may also become overloaded if it is required to supply the site load and this reactive current. The facility electrical designer should evaluate this situation and should specify limits on the capacitor leakage current or require power factor compensation, as necessary.

Furthermore, the presence of filter reactance will cause a phase shift between the line voltage and the load voltage. This shift is generally not a concern in the commercial power line application. It can be a major problem, however, in a synchro transmitter and receiver circuit unless compensation is provided.

The filter/ESA assembly can be a generator of harmonics of the power line frequency. One potential cause is undersized inductors, with nonlinear impedance characteristics at currents below the full-load value. Another possible source is voltage clipping by an improperly chosen MOV, which begins to conduct significantly at the crest of the waveform. These design deficiencies can be avoided with harmonic distortion performance limits and quality control checks in the filter/ESA specifications.

When other harmonic sources such as power converters are present in the system, the filter will enhance the current waveform distortion. This occurs because the filter capacitive impedance to ground is lower at the harmonic frequencies. If the effects are excessive, harmonic control techniques must be implemented (reference 12–23).

Finally, the filter reactance form resonances with other reactive elements in the distribution lines and site loads. The system will ring at these natural frequencies, with possibly harmful results, when excited by impulse-like transients caused by faults, switching, lightning, or HEMP. It is generally not possible to accurately predict the frequencies or magnitudes of the transient behavior. Therefore, power quality monitoring of the system is recommended. As a minimum, a post-installation check of the power quality should be required.

All of the above effects are aggravated by a cascade arrangement of filters in series. Therefore, filtering requirements for other disciplines such as TEMPEST and electromagnetic interference must be coordinated with the HEMP filtering needs. A single filter should be used, whenever possible, to meet all of these requirements.

Design of the power distribution to address these system-level issues is outside the scope of this handbook. These problems and techniques for their solution are treated in military power system design guides, such as references 12–24 through 12–26. However, the filter bypass switch recommended in MIL-HDBK-411 (reference 12–26) should not be installed at HEMP-protected facilities.

Various physical and mechanical, electrical, and environmental characteristics of the candidate devices must be evaluated. Physical and mechanical characteristics include mounting configuration, size and weight, and terminal strength. Some important filter electrical characteristics are voltage drop, insulation resistance, dielectric withstanding

voltage, and overload ratings. ESAs should be chosen to provide protection against the applicable lightning threat, as well as HEMP. It is particularly important that the devices be designed and tested for satisfactory operation under the expected environmental conditions where they will be installed. The sample filter/ESA specification in appendix A identifies many of these types of issues.

Different filter manufacturers use slightly different capacitor and inductor values to build comparably rated devices, and they may also use slightly different circuit configurations. The capacitive-input filter and the inductive-input filter analyzed in 12.1.3.4 (see figure 84) and 12.1.3.5 (see figure 89), respectively, are typical, however. These two designs are the bases for the performance discussion presented below.

The charge or current impulse of the 4000 A wire-to-ground HEMP short pulse is given by:

$$Q = \int^{\infty} I(t)\ dt = 2.9\ mC \tag{14}$$

If this charge is injected into the filter input terminals, the impulse response of the capacitive-input filter is such that its residual peak current is somewhat greater than the 10 A limit established by MIL-STD-188-125 (see 12.1.3.4). In order to meet this requirement, therefore, a surge arrester is necessary to shunt part of the charge of the short pulse transient to ground.

It is important to recognize that the surge arrester can only reduce the charge or impulse into the filter input terminals if it conducts during the time that the short pulse is applied. For this capacitive-input filter, the input capacitor has a value of 60 μF. This capacitor can absorb the entire charge of the short pulse at a peak voltage given by

$$V \approx \frac{Q}{C} = \frac{2.9 \times 10^{-3}}{6.0 \times 10^{-5}} = 48.3\ V \tag{15}$$

Therefore, the input capacitance will hold the voltage below the ESA conduction level if the surge arrester is placed directly across the filter terminals.

To benefit from the presence of the ESA, there must be sufficient inductance between the surge arrester and the filter input terminals to allow ESA conduction voltage to be developed. Figure 103 shows the variation of the current impulse delivered to the filter as a function of this series inductance. The maximum allowable impulse levels into the inputs of the two sample filter designs, if the residual peak currents are to be less than 10 A into a 2 Ω resistive load, are also shown. The waveform of the current through the load will be similar to that calculated in 12.1.3.4 (see figure 87), and the amplitude will be directly proportional to the filter input impulse.

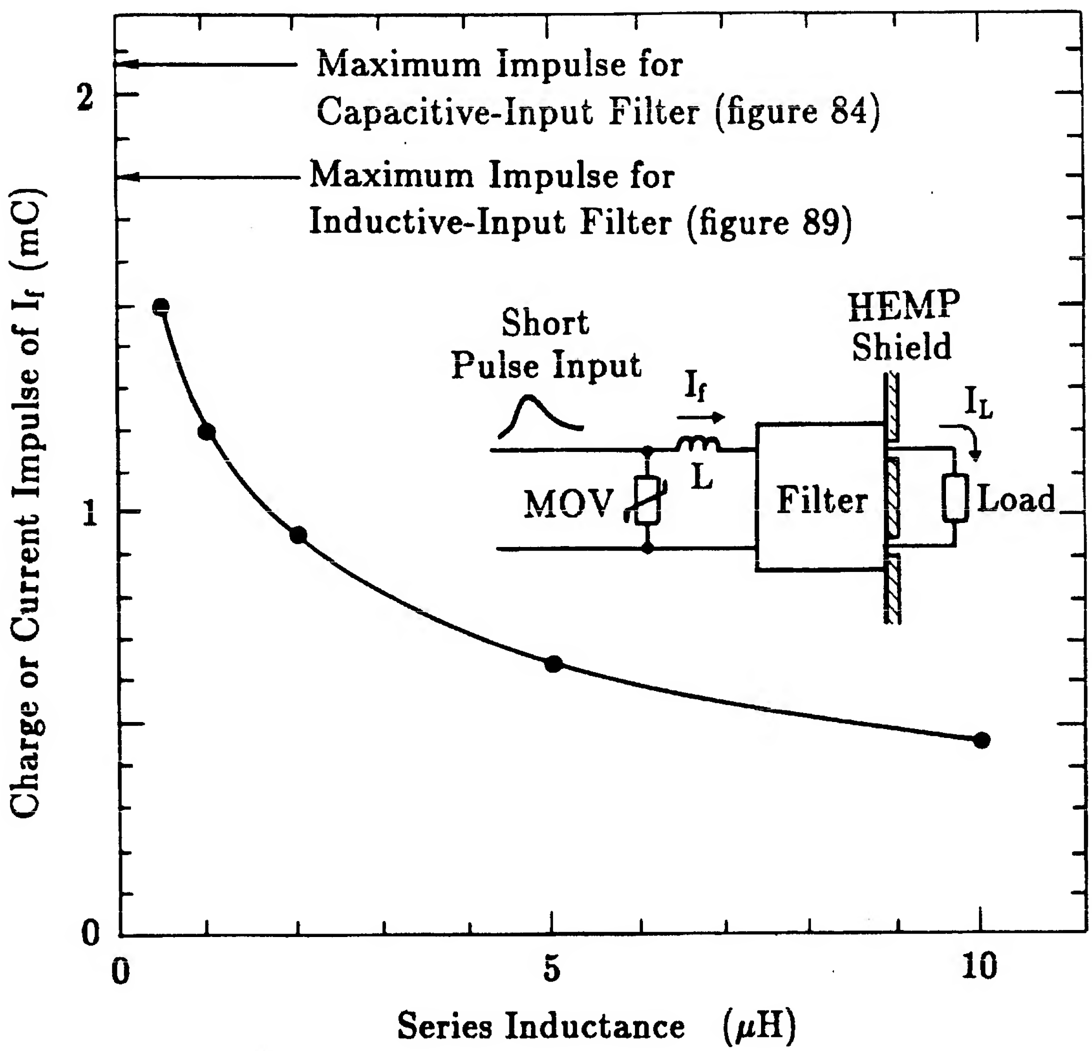


FIGURE 103. Variation of current impulses into filter with series inductance.

The data in figure 103 shows that an inductance of 1 μH is more than sufficient to meet the MIL-STD-188-125 residual internal peak current requirement. The series inductor must be capable of carrying the rated full-load current and withstanding the transient voltage developed across it. Inductors with these ratings are not readily available from suppliers, but they can be built in the shop or obtained commercially by special order. Alternatively, they can be constructed from about 1 m (3.3 ft) of power cable or bus bar. In the latter case, the 1 -μH inductor may be a straight bus bar, supported at one end by the filter terminal and the other end by the connection post or ESA terminal. A single loop of cable, approximately 0.3 m in diameter, can also be used for the inductor. It is important to identify the inductor as an HCI and to install it in a manner that it will not be modified or removed by maintenance personnel.

After a filter has been chosen for the commercial power line POE protective device, the designer should calculate the required inductance. In most cases, a 1 -μH inductance will be found to be adequate.

In addition to the residual peak current limit (10 A), MIL-STD-188-125 places limits on the rate of rise of the current (10^{+6} A/s), its rectified impulse (10^{-2} A-s), and its root-action (0.16 A- $\sqrt{s}$). . The residual rate of rise of the load current depends on the attenuation at frequencies in the 100-1000 MHz range. Power filters with at least 100 dB insertion loss over this range will satisfy the residual peak current requirement. These filters with surge arresters should easily meet the residual rectified impulse and root-action requirements. A time-domain circuit analysis code is very useful for evaluating the performance of the filter and surge arrester design.

One may also specify inductive-input filters to ensure that the surge arrester will conduct. This should be approached cautiously, however, since failure of the surge arrester will cause the full open-circuit voltage--200 kV or more-to be impressed across the filter terminals. Because the filter terminal and inductor insulation are not designed to withstand such voltages, the HEMP-induced voltage may damage the filter. In short, failure of the surge arrester may lead to failure of the filter, leaving the facility unprotected. With capacitive-input filters, however, failure of the surge arrester does not induce failure of the filter, because the filter input capacitance can absorb the entire short pulse without over-stressing insulation. The residual peak current increases to slightly above the allowable level, but very effective protection remains after loss of the surge arrester. Therefore, the use of inductive-input filters for HEMP protection of long lines is recommended only when the designer provides redundant overvoltage protection for the filter.

12.3.1.3 Intermediate pulse treatment. The combination of a surge arrester and filter is also effective in reducing the rate of rise and amplitude of the internal response

during the first part of the intermediate pulse. However, the filter becomes transparent to the intermediate pulse after a few milliseconds.

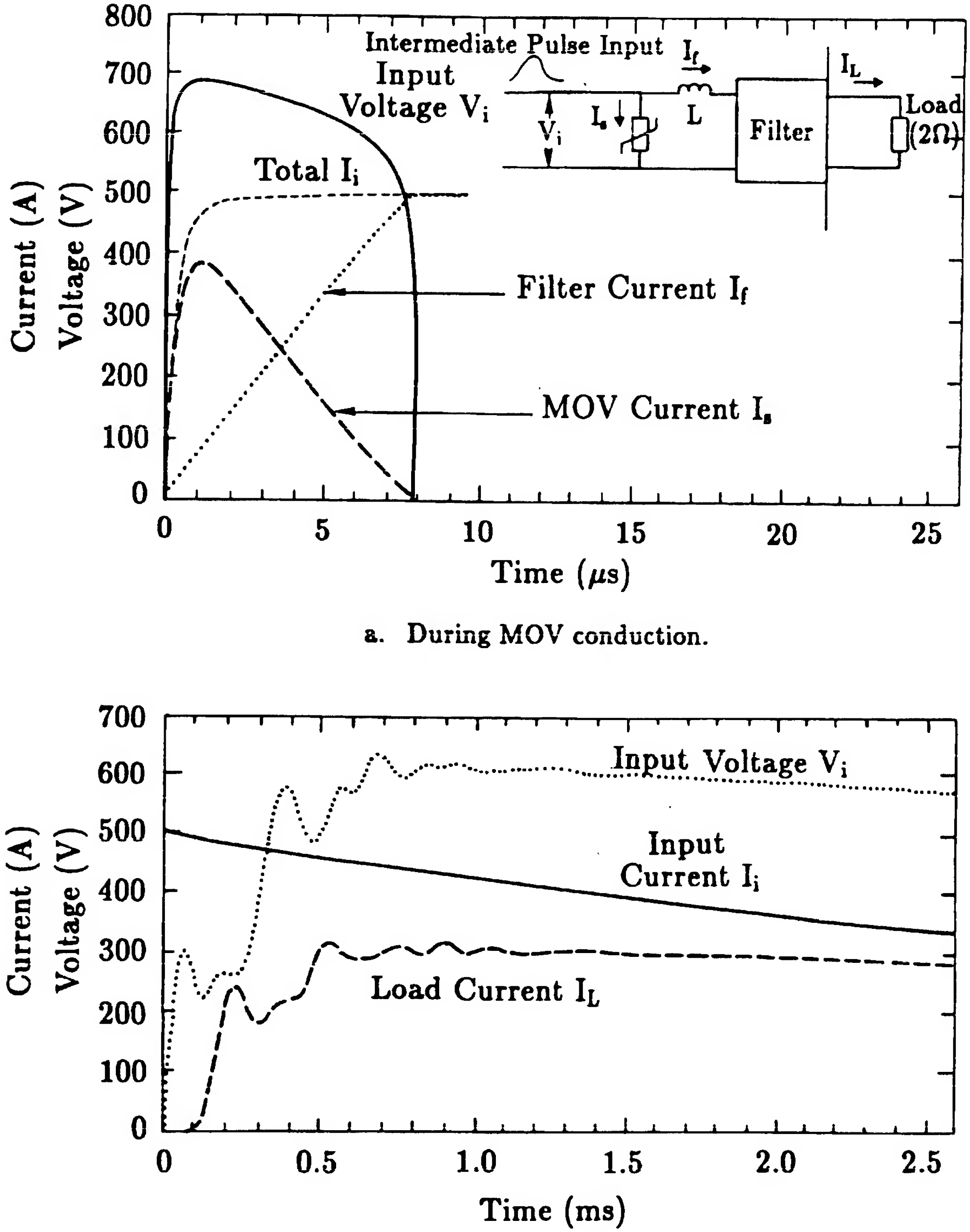
The results of a calculation of the intermediate pulse response of a filter/ESA are presented in figure 104. The surge arrester in this example is an MOV; the filter is the same capacitive-input device analyzed for the short pulse, with a small inductance in the line between the ESA and filter input. The load is a 2-Ω resistance. The HEMP-induced voltage at the input to the protective device initially builds up to a value sufficiently large to cause the MOV to conduct, because of the high-frequency impedance of the inductor. Within about 10 μs, however, virtually all of the current is flowing into the filter. The voltage rapidly decreases to a value determined primarily by the charge on the capacitive elements in the filter, and the surge arrester conduction ceases as indicated in figure 104a. After a few milliseconds, the capacitors are charged to the output voltage of the source. The current in the load then approaches the total source current, as shown in figure 104b.

The energy dissipated in the MOV in this example was only 163 J. Thus, out of the 1800 J that would have been delivered to the 2 Ω load without the MOV and filter, over 1600 J is delivered to the load with the filter and MOV installed. The filter and MOV are not very effective in protecting the load, but they will not be damaged by the intermediate pulse.

The system is also required to survive and operate when the intermediate pulse is impressed on the lines outside the barrier. It is not known whether the equipment inside the shield can tolerate the intermediate pulse residuals that are passed by the filter and MOV. However, the treatment required for long pulse protection can also be effective in suppressing the later portions of the intermediate pulse.

12.3.1.4 Long pulse treatment. As with the intermediate pulse, the principal requirement for the long pulse is that the system must tolerate it without degradation. Neither the system nor the barrier element can be damaged. The effect of the long pulse on the system is not known. However, the action and charge transfer associated with it are enormous, and it would not be surprising to find that some unprotected systems are damaged by the long pulse. Unless the entire system is known to be immune to the long pulse, it is required that protection against it be incorporated into the barrier design.

The long pulse flowing into the facility on the power conductors is of concern because its large currents are limited only by the dc resistance of motors, transformers, and other windings of typical 60 Hz loads. Thus the long pulse on the power conductors is a threat to critical motors and transformers in the facility unless it is interrupted. Similarly, the



a. During MOV conduction.

b. After MOV conduction.

FIGURE 104. Filter/MOV response to the intermediate pulse.

long-pulse current on long communication cables may be difficult to control unless it is interrupted.

The recommended barrier element for interruption of the long pulse is a transformer configured for common-mode rejection. For three-phase service, the distribution transformers can perform this barrier function if the primary side is delta connected, as illustrated in figure 105. Since the delta winding is an open circuit to the long pulse, virtually none of the long pulse will be coupled to the secondary windings. With the delta primary, the secondary could be either delta or wye-connected, but for most facilities the wye-connected secondary will be preferred for grounding and safety.

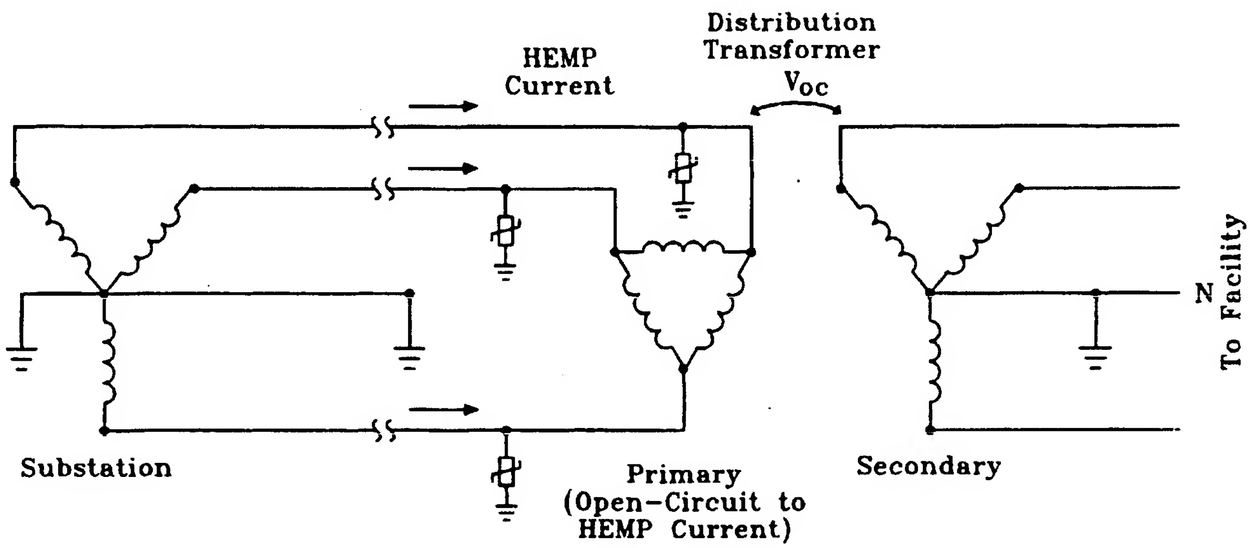


FIGURE 105. Distribution transformer in configuration to serve as the long-pulse barrier.

The distribution line, transformer, and building grounds must be configured in a manner to ensure that the overhead line long pulse current is not shunted onto the neutral conductor at the secondary side of the transformer. To provide effective isolation, it is recommended that the distribution line lightning shield conductor be terminated as far from the facility as practical at the last pole. As a minimum, the separation between this last ground in the distribution system and the facility must be at least 15.2 m (50 ft) to provide the buried section required by MIL-STD-188-125. The underground run is to be made by direct burial of the insulated phase conductors or in plastic (nonconducting)

conduit, as shown in the overall configuration diagram of figure 106. The same protection approach can be applied to an underground distribution system by treating the tap point as the last set of poles.

Because the transformer's delta-connected primary is an open circuit to the long pulse induced by HEMP, the entire open-circuit voltage of the long pulse will appear between the windings of the transformer. For the long pulse, this open-circuit voltage is only about 1000 V. This is well below the basic insulation level for distribu on transformers, which is typically about 10 times the rated primary voltage. These parts of the system must also tolerate (or be protected against) the short and intermediate pulses. The open-circuit voltage of the intermediate pulse is 25 kV or more, and that of the short pulse is 200 kV or more. The short pulse open-circuit voltage exceeds the basic insulation level of the transformer and buried cable. Thus it is prudent to install surge arresters to protect the transformer and cable from the short pulse, lightning, and other large transients.

The installation of surge arresters must be done in a manner such that the following are accomplished:

a. The pothead and underground cable are protected against insulation breakdown.

b. The primary windings are protected from transient overvoltage.

c. The primary circuit remains isolated from the secondary at late times.

d. The transient voltage between primary and secondary is limited.

To achieve these goals, it is recommended that MOV lightning arresters be installed at the pothead on the last pole and between the primary terminals and the case. The primary surge arresters must not be activated by the intermediate and long pulses. For isolation of the primary lines from the facility during the intermediate and long pulses, it is essential that the surge arresters be nonconducting at times greater than 1 ms after the short pulse arrives. Because MOVs extinguish promptly as the applied voltage decreases below the conduction threshold, it is recommended that MOV lightning arresters that do not conduct more than 1 A at 25 kV be used for the primary surge arresters. Figure 107 shows the transformer schematic, and figure 108 shows the low-inductance mounting of the surge arrester on the transformer case adjacent to the bushing of the protected primary terminal.

The installation of the MOV lightning arresters at the potheads at the last pole is illustrated in figure 109. These lightning arresters are required to protect the potheads and

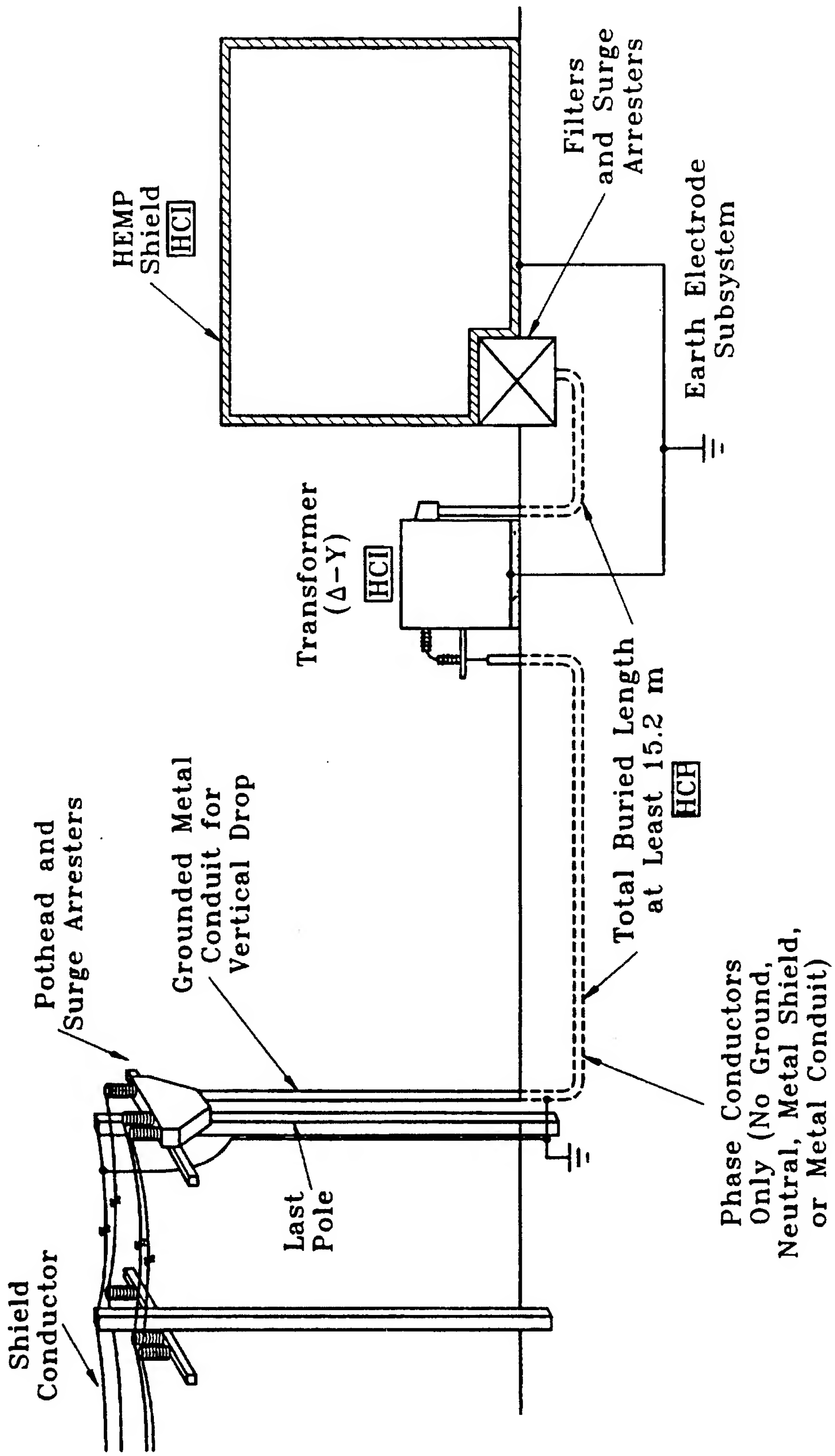


FIGURE 106. Overall arrangement of power service.

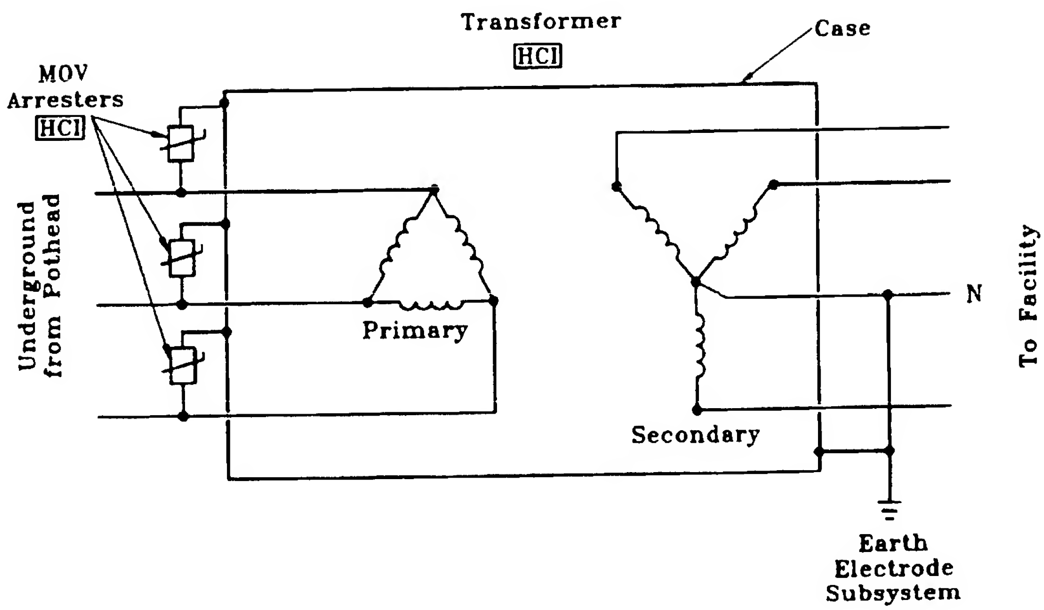


FIGURE 107. Schematic diagram of distribution transformer configuration.

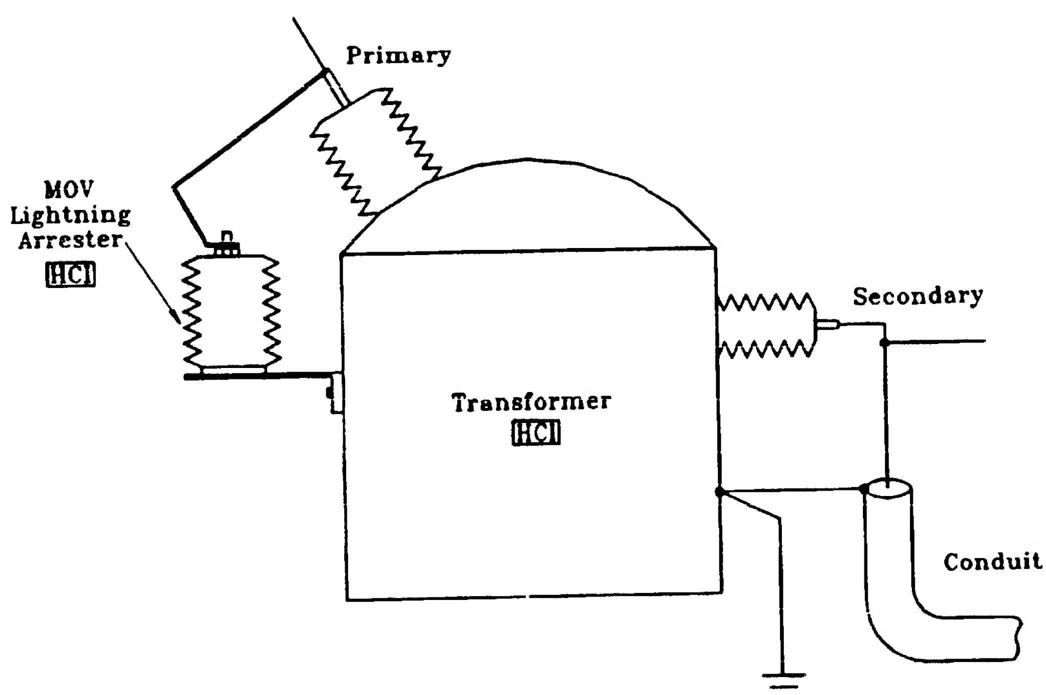


FIGURE 108. Installation of MOV lightning arrester on transformer.

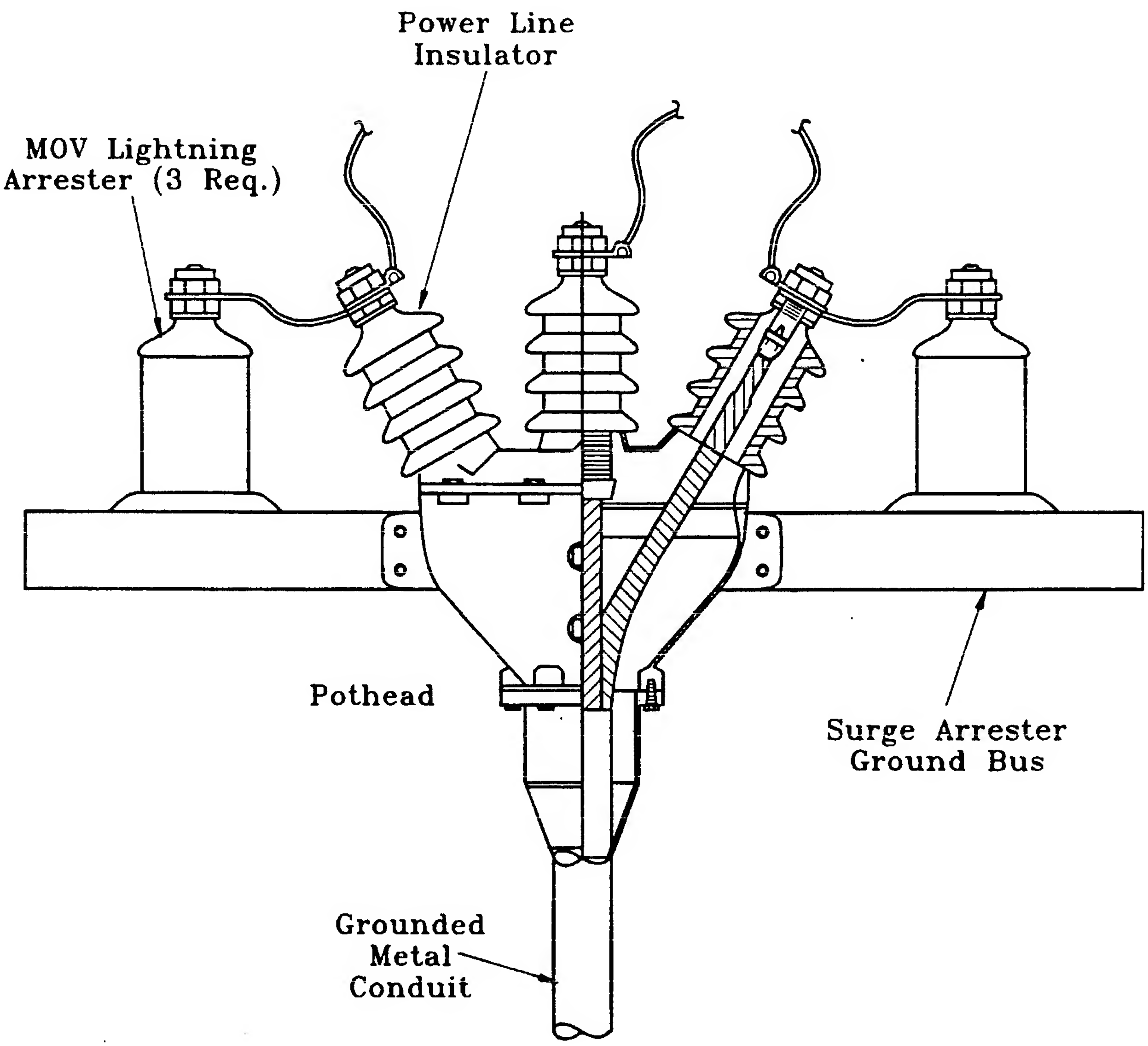


FIGURE 109. Installation of MOV lightning arrester at last pole.

the underground cable insulation from lightning and other surges. They are not hardness critical items.

Grounding the transformer case is necessary for safety, as is grounding the metal conduit for the service drop at the last pole (see figure 106). Grounding the transformer case and secondary neutral as shown in figure 107 also permits the MOV lightning arresters on the transformer primary to limit the winding-to-case and winding-t-winding voltages. Additional low-voltage MOVs are not required at the secondary terminals if low-voltage surge arresters are installed at the filter input terminals as discussed in 12.3.1.2 and illustrated in MIL-STD-188-125. However, one way of ensuring sufficient series inductance between the filter terminals and the surge arresters is to install them at the transformer.

12.3.1.5 Hardness critical items in power feeder protection. The hardness critical items in the power feeder protection are illustrated in the integrated power feeder protection diagram shown in figure 110. They include:

a. The distribution transformer

b. The primary-side MOV lightning arresters for the transformer (figures 107 and 108)

c. The filters and low-voltage surge arresters at the filter input terminals (or at the transformer secondary terminals)

In addition, the delta connection of the distribution transformer primary is a hardness critical feature. The 15.2-m (50-ft) underground section of the feeder cable is also hardness critical (see figure 106).

12.3.2 Treatment of intrasite facility power POEs.

12.3.2.1 MIL-STD-188-125 requirements for intrasite power line POEs. Mission-essential equipment outside the facility HEMP barrier must be supplied with protected power from the facility. These loads might include heat exchangers, antenna deicers, intrusion alarms, and various pumps, motors, and sensors. Although these loads are outside the main building, they must function even though commercial power is off and HEMP stresses are impressed. The requirements of MIL-STD-188-125 for this class of electrical POEs are as follows:

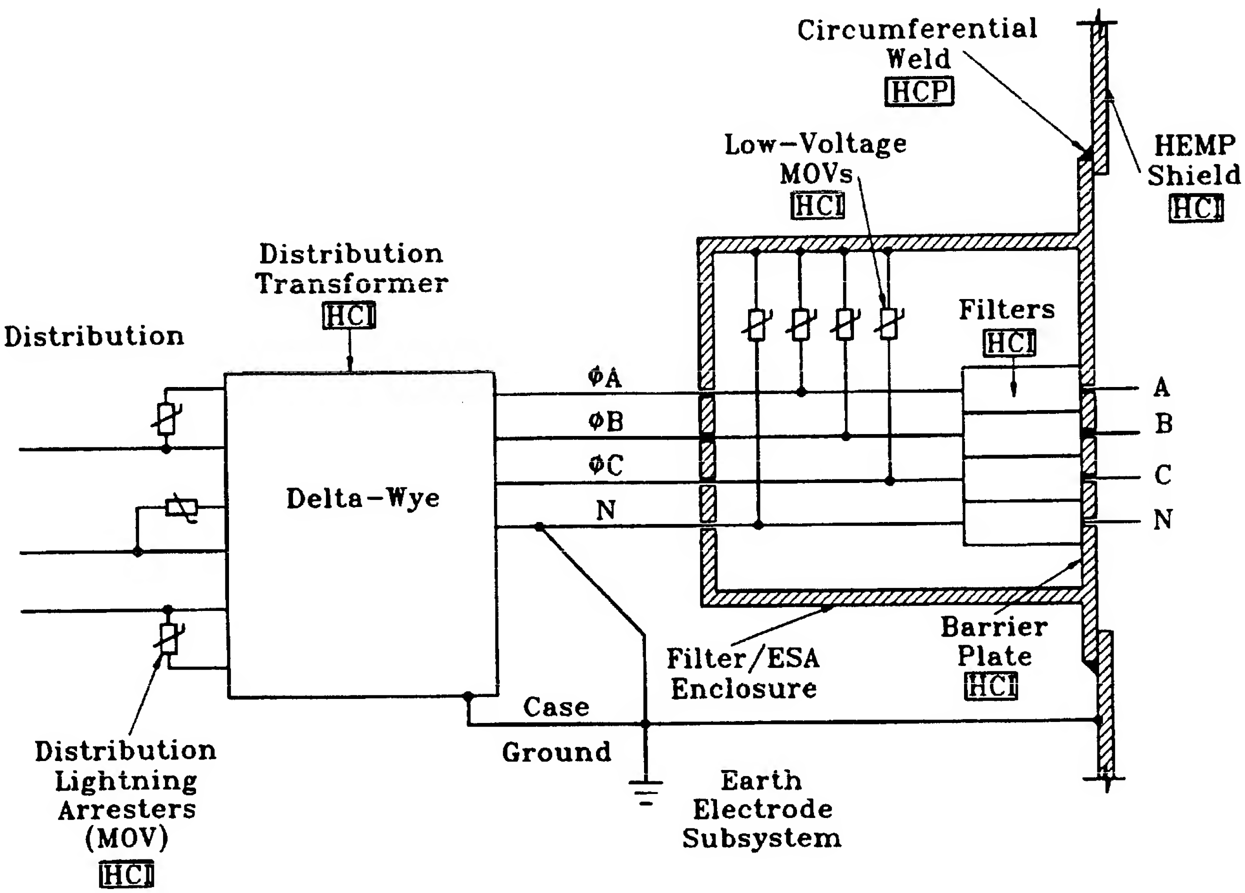


FIGURE 110. Integrated power feeder protection.

5.1.7.5 Other electrical power feeder FOES. A transient suppression/attenuation device shall be provided on each penetrating conductor of electrical power feeder POEs which supply internal power to equipment outside the electromagnetic barrier. As a design objective, internal power should be supplied only to MEE outside the electromagnetic barrier. Nonessential equipment outside the barrier should be powered from an external source.

5.1.7.5.1 Electrical power POE protective device requirements. A 4000 A pulse with 10 ns risetime and 500 ns FWHM, occurring on a penetrating conductor at the POE protective device external terminal, shall produce a residual internal transient stress no greater than 10 A and shall not cause device damage or performance degradation.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals which it is required to pass, a special protective volume shall be established (see 5.1.8.9.2).

[4] Common mode pulse withstanding requirements, waveform details of the injected pulses, additional constraints on the residual internal transient stress, and circuit test configuration information are contained in PCI test procedures of appendix B.

These local circuits are not subjected to the late-time currents that may drive the long distribution lines supplying commercial power to the facility (unless these late-time currents are allowed to flow into and through the facility). An early-time HEMP stress similar to the short pulse will occur if all or part of the external circuit is exposed to the HEMP environment. Circuits that are not shielded may be subject to insulation damage and other failures due to the large voltages induced by the early-time HEMP. Therefore, it is strongly recommended that power circuits for external mission-essential equipment be shielded with metal conduit. Additional guidance for MEE requiring SPMs is provided in section 14.

12.3.2.2 Penetration protection for intrasite facility power POEs. Penetration protection is used to protect the facility against the HEMP transients induced on external power circuits. However, this protection will not ensure that the external circuits survive. In the interest of minimizing the number of penetrating conductors and the number of hardness critical items that must be tested and maintained, nonessential loads should not be supplied from internal power sources.

Penetration protection to protect the facility against transients coupled to external power conductors can be obtained with the low-voltage surge arresters and filters described

in 12.3.1.2. External circuits drawing much less than 100 A should use filters with lower current ratings. These filters with lower current ratings generally have a larger series inductance and a smaller shunt capacitance than those with high current ratings (for the same 100 dB insertion loss specification). Nevertheless, each application should be evaluated to verify that the reactive leakage current will not overload the circuit breaker or power supply. Requirements to preserve phase across the filter should also be checked. As needed, power factor compensation should be provided.

The surge arrester is required to protect the filter, as well as to reduce the impulse response of the filter. The charge transfer of 2.9 mC and action of 6 J/Ω are quite modest and can be accommodated by a broad variety of commercial MOVs.

12.3.3 Treatment of intersite telephone audio/data line POEs.

12.3.3.1 MIL-STD-188-125 requirements for intersite audio/data line POEs.

> 5.1.7.6 Audio and data line POEs.
>
> 5.1.7.6.1 Standard audio and data lines. All standard voice and data lines, whether shielded or unshielded, shall be converted to fiber optics outside the electromagnetic barrier and shall penetrate the facility HEMP shield on all-dielectric fiber optic cables. Electro-optic equipment outside the electromagnetic barrier shall be protected using special protective measures (see 5.1.8.1), if the associated audio or data line is mission-essential. The fiber optic cable POE shall be protected with a waveguide-below-cutoff protective device.
>
> 5.1.7.6.1.1 Fiber optic waveguide dimensions. The inside diameter of a fiber optic waveguide-below-cutoff shall not exceed 10 cm (4 in). The length of the waveguide shall be at least jive times the inside diameter of the waveguide-below-cutoff.
>
> 5.1.7.6.1.2 Fiber optic waveguide construction. All joints and couplings in the waveguide shall be circumferentially welded or brazed, and the waveguide-below-cutoff shall be circumferentially welded or brazed to the facility HEMP shield at the POE. No conductors or conducting fluids shall be permitted to pass through the waveguide; the waveguide shall be filled or its ends shall be capped to prevent inadvertent insertion of conductors.

5.1.7.6.2 Nonstandard audio and data lines A transient suppression/attenuation device shall be provided on each penetrating conductor of shielded or unshielded nonstandard audio or data lines which cannot be practically converted to fiber optics. As a design objective, a maximum of 20 such nonstandard audio or data lines should penetrate the facility HEMP shield.

5.1.7.6.2.1 Nonstandard audio and data POE protective device requirements An $8000/\sqrt{N}$A or 500 A pulse with 10 ns risetime and 500 ns FWHM (where N is the number of penetrating conductors in the audio or data cable and the larger amplitude is chosen), occurring on a penetrating conductor at the POE protective device external terminal, shall produce a residual internal transient stress no greater than 0.1 A and shall not cause device damage or performance degradation.[4] A pulse of 500 A with 1 μs risetime and 5 ms FWHM and a pulse of 200 A with 0.5 s risetime and 100 s FWHM, at the POE protective device external terminal, shall not cause device damage or performance degradation.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals it is required to pass, a special protective volume shall be established (see 5.1.8.3.2).

[4] Common mode pulse withstanding requirements, waveform details of the injected pulses, additional constraints on the residual internal transient stress, and circuit test configuration information are contained in PCI test procedures of appendix B.

MIL-STD-188-125 is quite specific on the disposition of standard audio and data lines. The electrical signals must be converted to optical signals, which enter the facility on an all-dielectric fiber optic cable. 'Standard voice and data lines" are all intersite wire communication media for commercial and military voice or digital data transmission. This class includes local telephone service. Thus, all such communications cables entering from off-site and serving personnel and equipment in the facility must be converted to fiber optic lines for penetrating the HEMP shield.

The intent of this requirement is to minimize the number of hardness critical items in the primary HEMP barrier, by replacing many (perhaps hundreds) of POE protection devices for wires with a single fiber optic cable and waveguide-below-cutoff. However, the intermediate and long pulse currents on the exposed cable pose additional problems. Power must be supplied to the exterior optoelectronic converter, and the grounding must be provided in a manner which preserves the protection of the facility from late-time currents.

"Nonstandard" audio and data lines are intersite communication lines that have special operating characteristics which make the fiber optic conversion and transmission impractical. The use of such nonstandard lines should be avoided if possible. However, MIL-STD-188-125 provides for this case, where the use of nonstandard lines is necessary. The number of nonstandard lines should be kept to a minimum to keep the number of hardness critical items as low as possible. The design objective is fewer than 20 POEs (10 pairs).

Because these long lines are subject to the late-time effects of the intermediate and long pulses, some isolation in addition to the short pulse surge suppression and filtering will be required. Although the short pulse current is reduced by $\sqrt{N}$, where N is the total number of wires in the cable, for the 20-wire recommended maximum, this reduction factor is only 4.5.

12.3.3.2 Fiber optic isolation for audio/data lines.

12.3.3.2.1 Power for the optoelectronic converter. For the purpose of HEMP isolation, the optoelectronic converter must be outside the facility shield and supplied with power either from an independent source or from a protected source inside the barrier. If the fiber optic communication link is mission-essential equipment, the converter and its power supply must be enclosed within a special protective volume as illustrated in figure 111. Operating power for mission-essential optoelectronic converters must be supplied from the facility HEMP-hardened electrical power generation and distribution system or from a separate HEMP-hardened electric power system outside the building.

If the fiber optic link is not mission-essential equipment, the external converter should not be powered from the facility HEMP-hardened power system. This case, employing the commercial source, is illustrated by figure 112a.

When the link is MEE and the external converter requires HEMP-protected power from the facility, the installation should be as shown in figure 112b. The hardness critical isolation transformer prevents intermediate and long pulse currents from flowing between the converter shield and the primary HEMP barrier along the power feeder conductors, so that the POE protective devices at both ends are required to satisfy only the short pulse suppression/attenuation specifications. If the incoming audio/data cable is intrasite, however, intermediate and long pulse isolation will be required at the penetration of the converter special protective barrier. Subsection 12.3.3.3 discusses audio/data line POE protective devices for this application.

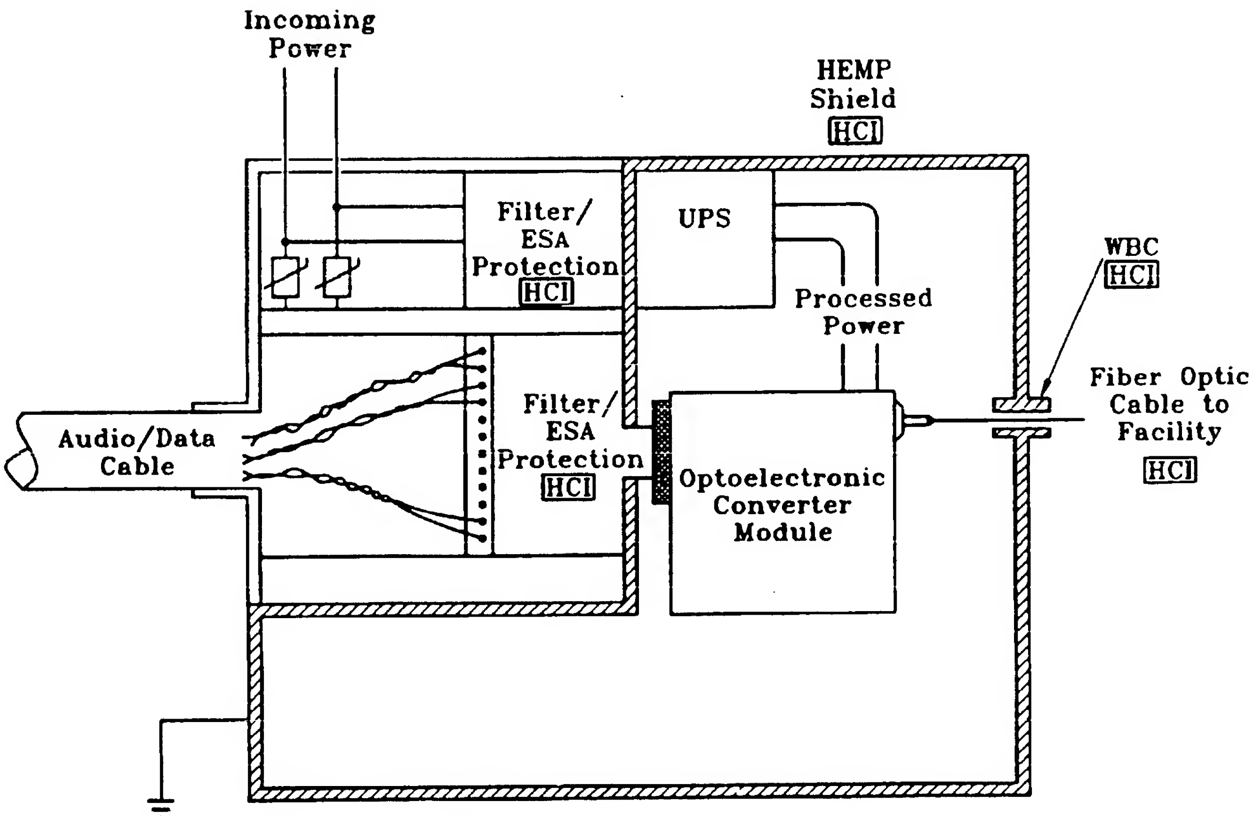
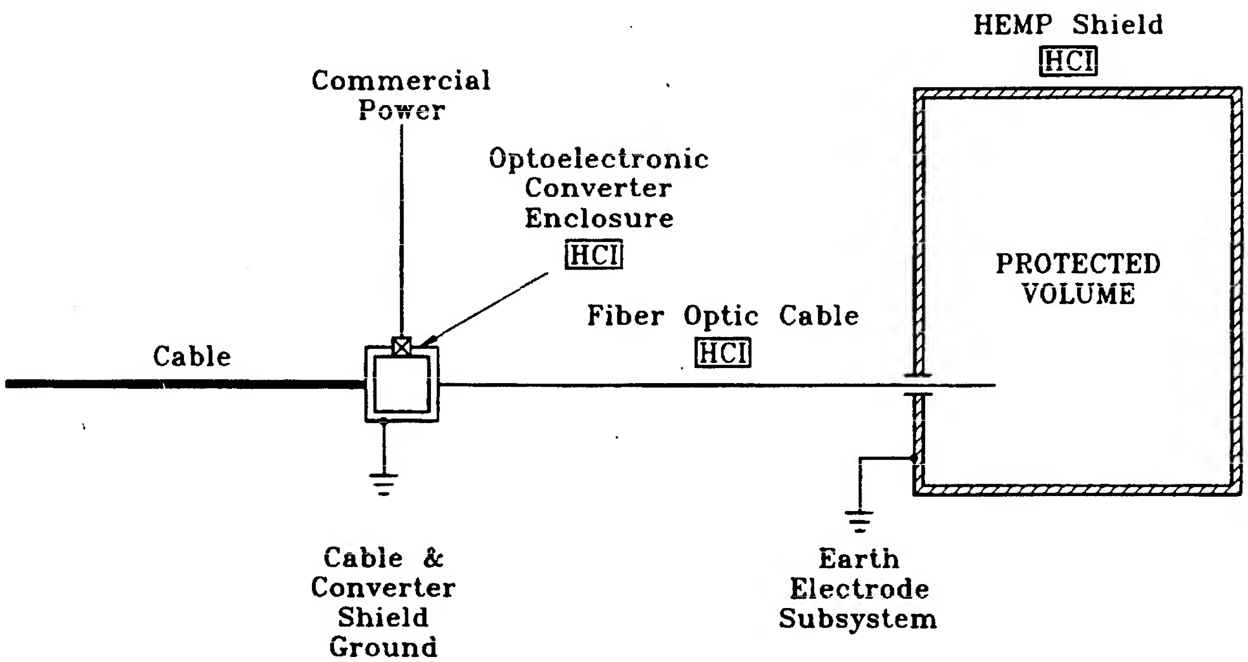
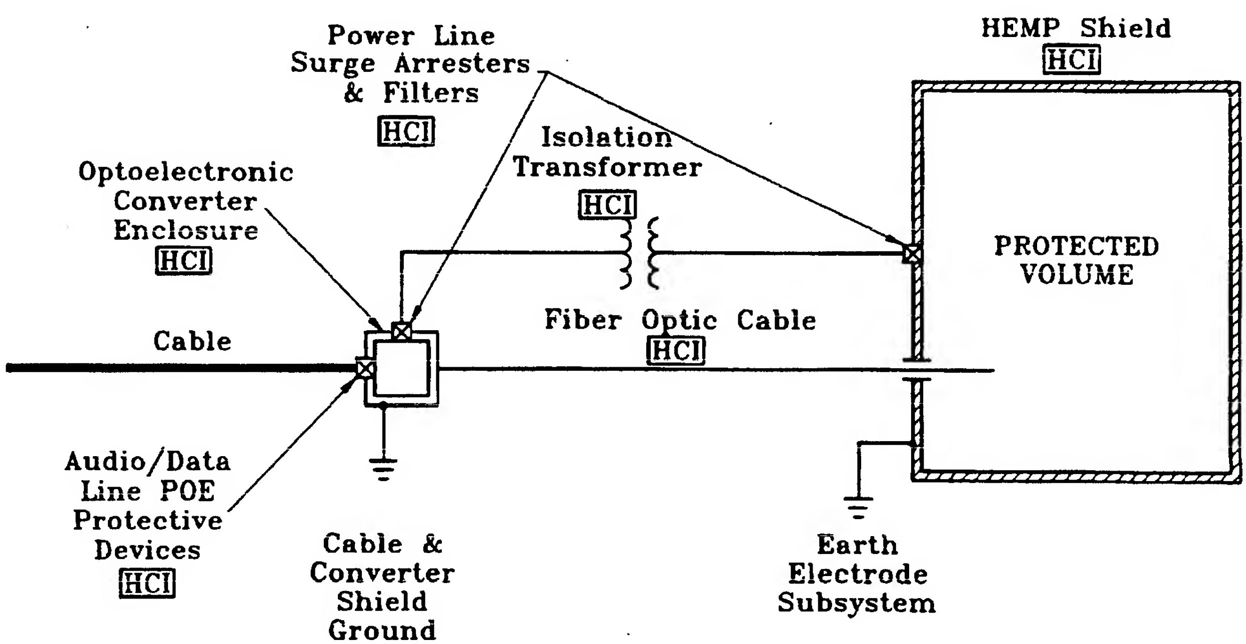


FIGURE 111. Special protective measures for optoelectronic converter on an audio/data cable.



a. **Commercial power.**



b. **Powered from facility.**

FIGURE 112. Power and grounding arrangement for optoelectronic converter on an audio/data cable.

12.3.3.2.2 Grounding. Intermediate and long pulse transients that arrive on the intrasite audio/data cable may be intentionally or inadvertently shunted to ground on the external optoelectronic converter enclosure shield. Because the building HEMP shield is a much better conductor than the soil, the large cable currents injected into the earth at this location will flow to the facility barrier if a hard-wired connection exists. To prevent this occurrence, separate grounds for the converter shield and facility are recommended. If practical, the separation distance should be about twice the largest horizontal dimension of the building.

12.3.3.3 Penetration protection for nonstandard audio and data lines.

12.3.3.3.1 Short and intermediate pulse protection. Protection against the short pulse and leading edge of the intermediate pulse can be achieved with conventional filters and gas tube surge arresters. The low-voltage gas tube surge arrester has a very small electrode capacitance so that it does not load signal circuits significantly. Filters for telephone circuits carrying voice traffic (3 to 4 kHz bandwidth) or low data rate signals are widely available. These can be applied to HEMP protection if they meet, or can be modified to satisfy, the following requirements:

a. They must be functionally compatible with specific circuits of interest.

b. They must have a spark gap.

c. They must provide attenuation of HEMP transients, without affecting the normal. differential mode signals.

d. They must be mounted in an rf-tight enclosure (box, cabinet) with adequate isolation between input and output.

e. They must have the ability to withstand the HEMP transients.

Most telephone-type surge arresters (gas tubes) are rated for charge transfer of a few coulombs. Thus they will tolerate the short pulse and perhaps the intermediate pulse, but they are not designed to tolerate the long pulse.

When the data rate of the communication lines is high, filtering becomes more difficult and special designs may be required. In such cases, the filter can be designed to provide some limiting, followed by high common-mode rejection, without affecting the differential data signals. The remaining elements provide high frequency filtering of the residual HEMP transients (reference 12-8).

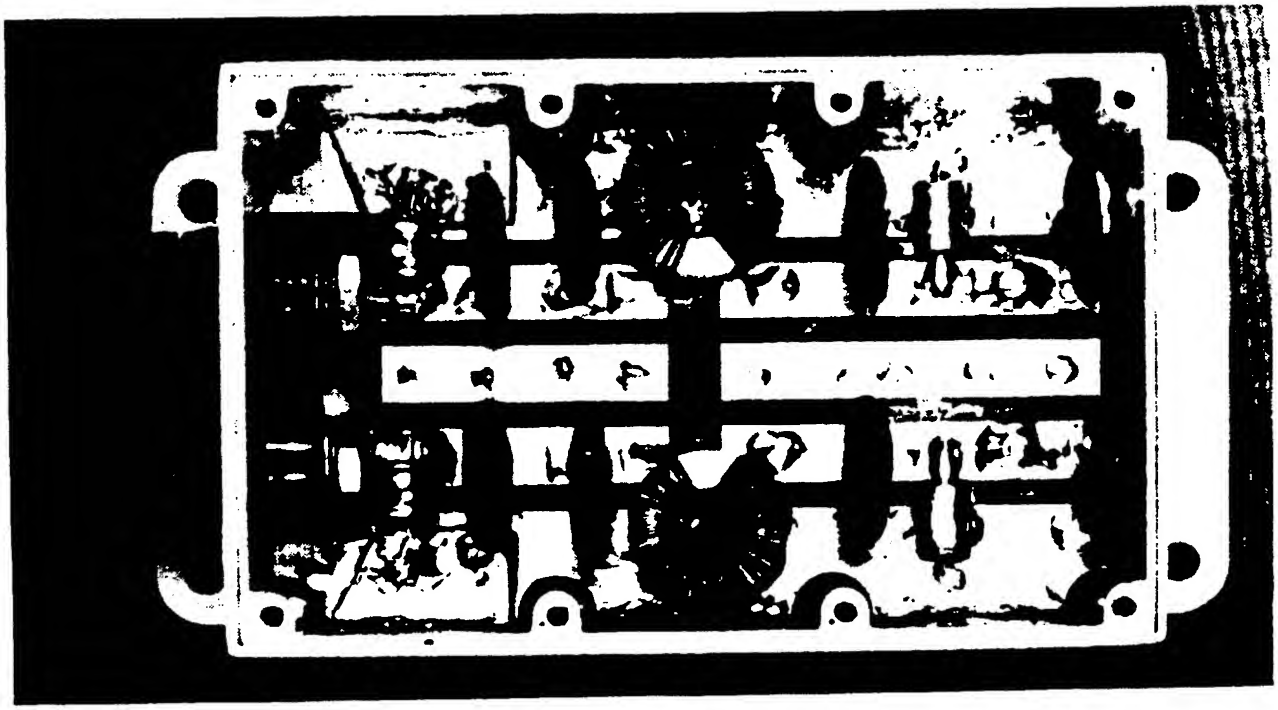
Figure 113 shows the schematic, layout, and specifications for one such dual wire (pair) high data rate, low-pass filter. Note the zero length leads on the spark gaps at the input terminals to the left of the photograph. Low-inductance "bus-bar" interconnects are provided for all other components.

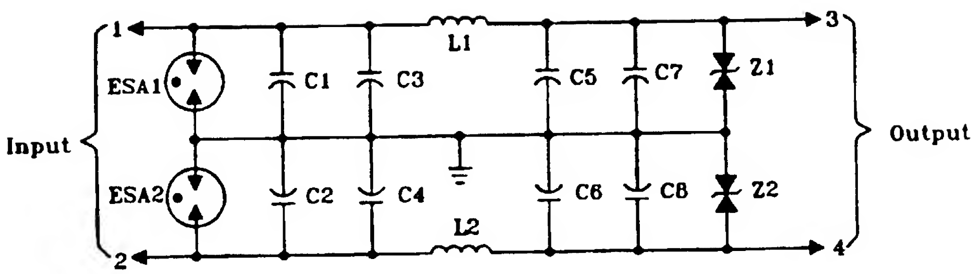
Figure 114 shows a prototype of a high data rate filter specially developed under DNA auspices for use in commercial telephone circuits. The filter unit handles one pair and mounts in a cabinet with excellent input/output isolation. The schematic is shown in figure 114 and features a bifilar-wound coil with high-voltage insulation for the common-mode rejection, a three-electrode spark gap for input limiting of either common-mode or differential signals (lightning or HEMP), and a multisection differential filter to attenuate the high frequencies that get past the spark gap. The spark gap has been tested to its failure threshold (75,000 A lightning-type surge). The filter functional performance has been demonstrated in active high data rate circuits, and the design has been approved by the user telephone utility. HEMP tests in both the common mode and differential mode verified the specified HEMP insertion loss.

12.3.3.3.2 Long pulse protection. As noted above, the telephone-type gas tube surge arresters cannot tolerate the charge transfer in the long pulse. The long pulse will also damage the inductors and perhaps the solder joints in filters such as those in figures 113 and 114. Therefore, it will be necessary to use isolation transformers with a common-mode insulation strength greater than a few kilovolts to block the long pulse and to protect the filter and low-voltage gas tubes.

A schematic diagram of a late-time protection design using an isolation transformer, with a gas tube to protect the transformer from the short and intermediate pulses, is shown in figure 115. The short pulse and the leading edge of the intermediate pulse will pass through the stray capacitances between the transformer windings. The transformer will block substantially all of the long pulse in the common mode and the differential mode. The isolation transformer must be compatible with the data rate and bandwidth of the communication line and must have an insulation strength (primary-to-secondary and primary-to-ground or case) of a few kilovolts.

The gas tube must be selected to fire below the transformer dielectric breakdown voltage, but preferably at a voltage greater than the open-circuit voltage of the long pulse. The gas tube should protect the transformer against the large voltages of the short and intermediate pulses, but it need not tolerate the very large charge transfer of the long pulse (if it extinguishes after the intermediate pulse). The gas tube should be chosen to extinguish with less than 1000 V applied. It is not desirable to have the gas tube





Circuit Configuration

TYPE: DUAL, HIGH DATA RATE
LOW-PASS FILTER

APPLICATION: TELEPHONE LINE
(PAIR PROTECTION)

TRANSMISSION DATA RATE: 19–50 kBit/s

PASSBAND (FLAT): dc 150 kHz (3 dB)

CUTOFF FREQUENCY (F_{CO}): 150 kHz

IMAGE IMPEDANCE: 70 Ω

ATTENUATION CHARACTERISTICS:
18 dB/OCTAVE, 60 dB/DECADE
EMP THREAT, 30 V PP MAX

CONFIGURATION: RF ENCLOSURE
WITH FEEDTHROUGH TERMINALS
BINDING POST TYPE (TWO PAIR)

SIZE: 14.3 cm L × 6.6 cm W × 7.1 cm H

WEIGHT: 680 g

FIGURE 113. Example of a HEMP filter for high data rate communications circuits.

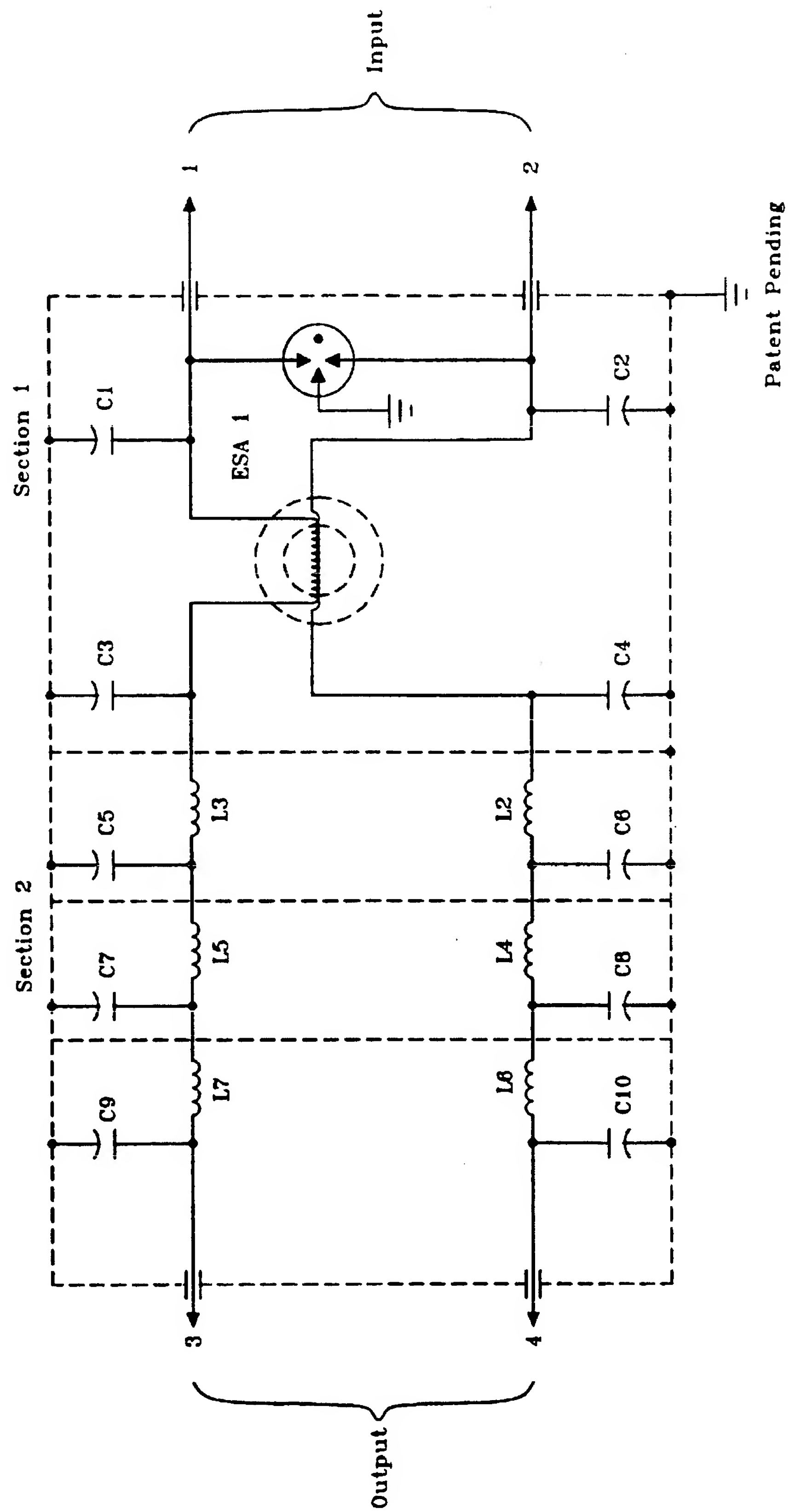


FIGURE 114. Schematic of DNA high data rate filter (reference 12-8).

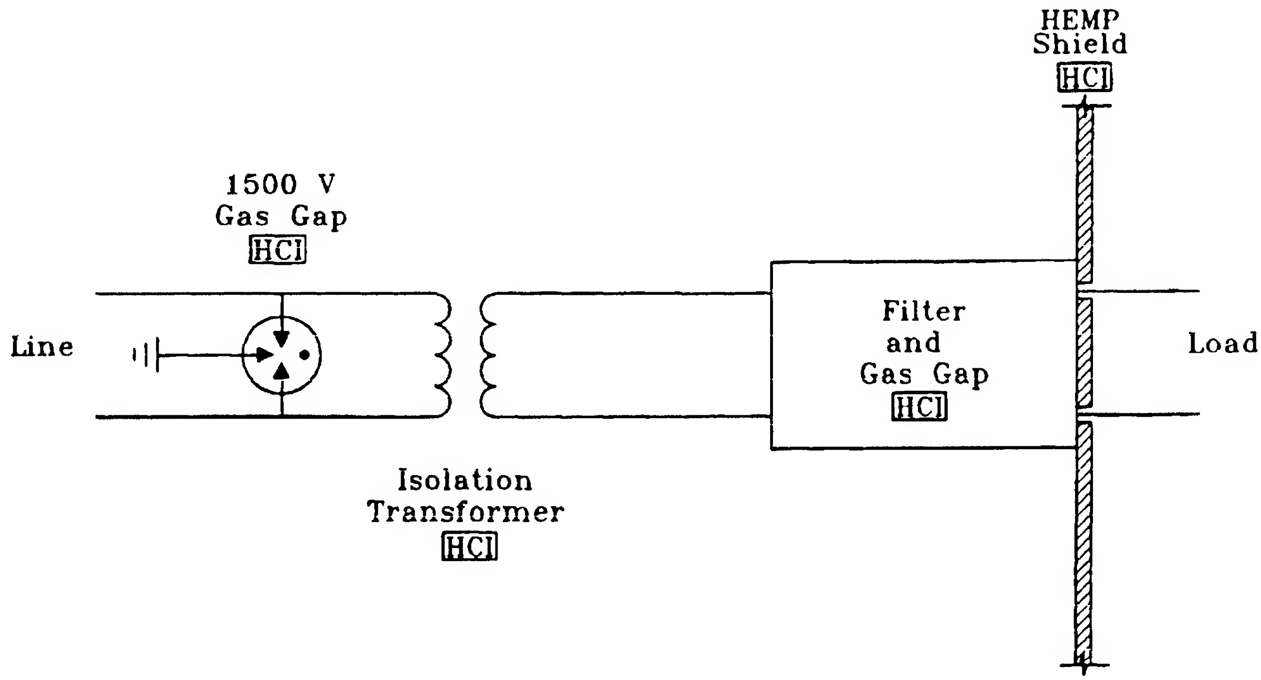


FIGURE 115. Isolation transformer for long pulse isolation (protected with a gas tube).

conducting during the long pulse, since this requires a very heavy-duty gap and it injects the long pulse current into the facility ground.

12.3.4 Treatment of intrasite control and signal line POEs.

12.3.4.1 MIL-STD-188-125 requirements for control/signal line POEs. The control and signal lines are primarily those conductors required to perform the station-keeping functions such as monitoring fuel supply levels, heat exchanger performance parameters, and outside weather. Low-power control circuits for actuating relays and solenoids may also be included.

Whenever practical, such control and signal lines should be eliminated. Possible methods include eliminating the need for the function, eliminating the need to bring the control or signal into the HEMP shielded area, enclosing the function entirely inside the protected volume, or using fiber optic, pneumatic, or other nonelectrical media for conveying the signal or control. When elimination is not practical, the following MIL-STD-188-125 requirements apply:

5.1.7.7 Electrical control and signal line POEs. A transient suppression/attenuation device shall be provided on each penetrating conductor of electrical control and signal lines, whether shielded or unshielded. As a design objective, the number of control and signal lines penetrating the facility HEMP shield should be minimized by use of alternate control techniques.

5.1.7.7.1 POE protective device requirements for control and signal lines operating at voltages less than 90 V. An $8000/\sqrt{N}$ A or 500 A pulse with 10 ns risetime and 500 ns FWHM (where N is the number of penetrating conductors in the control or signal cable and the larger amplitude is chosen), occurring on a penetrating conductor at the POE protective device external terminal, shall produce a residual internal transient stress no greater than 0.1 A and shall not cause device damage or performance degradation.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals it is required to pass, a special protective volume shall be established (see 5.1.8.3.2).

5.1.7.7.2 POE protective device requirements for control and signal lines operating at 90 V and higher. An $8000/\sqrt{N}$ A or 500 A pulse with 10 ns risetime and 500 ns FWHM (where N is the number of penetrating conductors in the control or signal cable and the larger amplitude is chosen), occurring on a penetrating conductor at the POE protective device external terminal, shall produce a residual internal transient stress no greater than 1 A and shall not cause device damage or performance degradation.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals it is required to pass, a special protective volume shall be established (see 5.1.8.3.2).

[4] Common mode pulse withstanding requirements, waveform details Of the injected pulses, additional constraints on the residual internal transient stress, and circuit test configuration information are contained in PCI test procedures of appendix B.

The intent of these requirements is to minimize the number of hardness critical items that must be tested, monitored, and maintained. If the control or signal line cannot be eliminated, it must be provided with sufficient surge suppression to limit the residual transient current to 1 A or less on circuits operating at 90 V and higher. For circuits operating at less than 90 V, the peak residual current must be 0.1 A or less.

12.3.4.2 Penetration protection for control/signal line POEs. The control and signal circuits are for the most part low-power and small bandwidth analog circuits. In addition, they are intrasite circuits which are not exposed to the long-lasting intermediate and late-time pulses. Thus, MOVs or gas tube surge arresters are suitable for most of these circuits. Low-pass, low-current electromagnetic compatibility filters may also be used.

12.3.5 Treatment of antenna line POEs.

12.3.5.1 MIL-STD-188-125 requirements for antenna line POEs. Antenna lines are coaxial or twinaxial transmission lines between antennas outside the HEMP barrier and the radio receivers or transmitters inside the barrier. The shields of these transmission lines must be bonded to the facility shield at the point-of-entry. The internal signal conductor lines must be provided with a transient suppression/attenuation element to prevent HEMP-induced transients on the antenna from propagating to the receivers and transmitters, where they may cause damage. For large antennas operating at HF and lower frequencies, there is a further concern that the induced voltages may be large enough to produce flashover at antenna terminals and transmission line connectors.

The requirements of MIL-STD-188-125 are thus directed toward cable shield bonding and transmission line transient suppression/attenuation. These requirements are as follows:

5.1.7.8 <u>Radio frequency antenna line POEs</u>. A transient suppression/attenuation device shall be provided on signal-carrying conductors of all penetrating radio frequency antenna lines. The antenna cable shields shall be circumferentially bonded to the facility HEMP shield at the POE.

5.1.7.8.1 Antenna line POE protective device requirements.

5.1.7.8.1.1 Signal conductor injection for receive-only antennas. A pulse of the prescribed waveform and amplitude, occurring on the signal-carrying conductor at the external terminal of a receive-only antenna line POE protective device, shall produce residual internal transients stresses no greater than 0.1 A on the signal-carrying conductor and shield and shall not cause device damage or performance degradation.[4] The pulse waveform and amplitude are determined by the lowest characteristic response frequency, f, which is 150/L MHz (where L is the largest dimension of the associated antenna in meters). The prescribed pulse is an 8000 A double exponential with 10 ns risetime and 500 ns FWHM, where the lowest characteristic response frequency is less than 2 MHz.[4] The prescribed pulse is a 2 MHz damped sinusoid with 2500 A peak current, where the lowest response frequency is 2 MHz to 30 MHz.[4] The prescribed pulse is a 30 MHz damped sinusoid with 900 A peak current, where the lowest response frequency is 30 MHz to 200 MHz, and a 200 MHz damped sinusoid with 250 A peak current, when the lowest response frequency is greater than 200 MHz.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals it is required to pass, a special protective volume shall be established (see 5.1.8.3.2).

5.1.7.8.1.2 Signal conductor injection for transmit antennas. A pulse of the prescribed waveform and amplitude, occurring on the signal-carrying conductor at the external terminal of a transmit-only or transceiver antenna line POE protective device, shall produce residual internal transient stresses no greater than 1 A on the signal-carrying conductor and 0.1 A on the shield and shall not cause device damage or performance degradation.[4] The pulse waveform and amplitude are determined by the lowest characteristic response frequency, f, which is 150/L MHz (where L is the largest dimension of the associated antenna in meters). The prescribed pulse is an 8000 A double exponential with 10 ns risetime and 500 ns FWHM, where the lowest characteristic response frequency is less than 2 MHz.[4] The prescribed pulse is a 2 MHz damped sinusoid with 2500 A peak current, where the lowest response frequency is 2 MHz to 90 MHz.[4] The prescribed pulse is a 30 MHz damped sinusoid with 900 A peak current, where the lowest response frequency is 30 MHz to 200 MHz, and a 200 MHz damped sinusoid with 250 A peak current, when the lowest response frequency is greater than 200 MHz.[4] If a POE protective device cannot be designed to satisfy the residual internal transient stress limits without interfering with operational signals it is required to pass, a special protective volume shall be established (see 5.1.8.9.2).

5.1.7.8.1.3 Shield injection. A 1000 A pulse with 10 ns risetime and 500 ns FWHM, occurring on the shield of a buried antenna cable at a point outside the electromagnetic barrier, shall produce residual internal transient stresses no greater than 0.1 A on the signal-carrying conductor and shield and shall not cause POE protective device damage or performance degradation.[4] For a nonburied antenna cable, an 8000 A pulse with 10 ns risetime and 500 ns FWHM on the shield at a point outside the barrier shall produce residual internal transient stresses no greater than 0.1 A on the signal-carrying conductor and shield and shall not cause POE protective device damage or performance degradation.[4] An antenna cable is considered buried when less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill and it terminates at a buried antenna. The cable is considered nonburied if at least 1 m (3.3 ft) of its total length is not covered.

[4] Common mode pulse withstanding requirements, waveform details of the injected pukes, additional constraints on the residual internal transient stress, and circuit test configuration information are contained in PCI test procedures of appendix B.

MIL-STD-188-125 requires antenna lines to be protected against the short pulse only. It is tacitly assumed that the intermediate and long pulses will not be applied to the antenna cables. Thus, no long lines--e.g. telephone or power—may be routed to antennas or antenna towers. The intermediate and long pulses must be sufficiently blocked at the facility so that the antenna cables cannot be indirectly driven by these pulses.

12.3.5.2 Penetration protection for antenna line POEs.

12.3.5.2.1 Shield bonding. The shields of rf cables entering the HEMP barrier must be properly bonded to the HEMP barrier at the penetration entry area, and the core wire must be protected with filters and ESAs. Solid-jacketed cable is preferred over braided shield cable outside the HEMP barrier because of the 100 percent coverage. The use of feedthrough connectors which are not welded, soldered or brazed at the PEA panel should have rf mesh gaskets between the washers and the shield wall. Installation specifications can be obtained from rf mesh gasket manufacturers.

The use of feedthrough connectors with star lockwashers on a clean metal panel provides a good bond for the cable shield and is convenient for installation and maintenance of the radio systems. This method is illustrated in figure 116. An alternative is to use bulkhead connectors as illustrated in figure 117. To achieve a low-resistance bond, it is

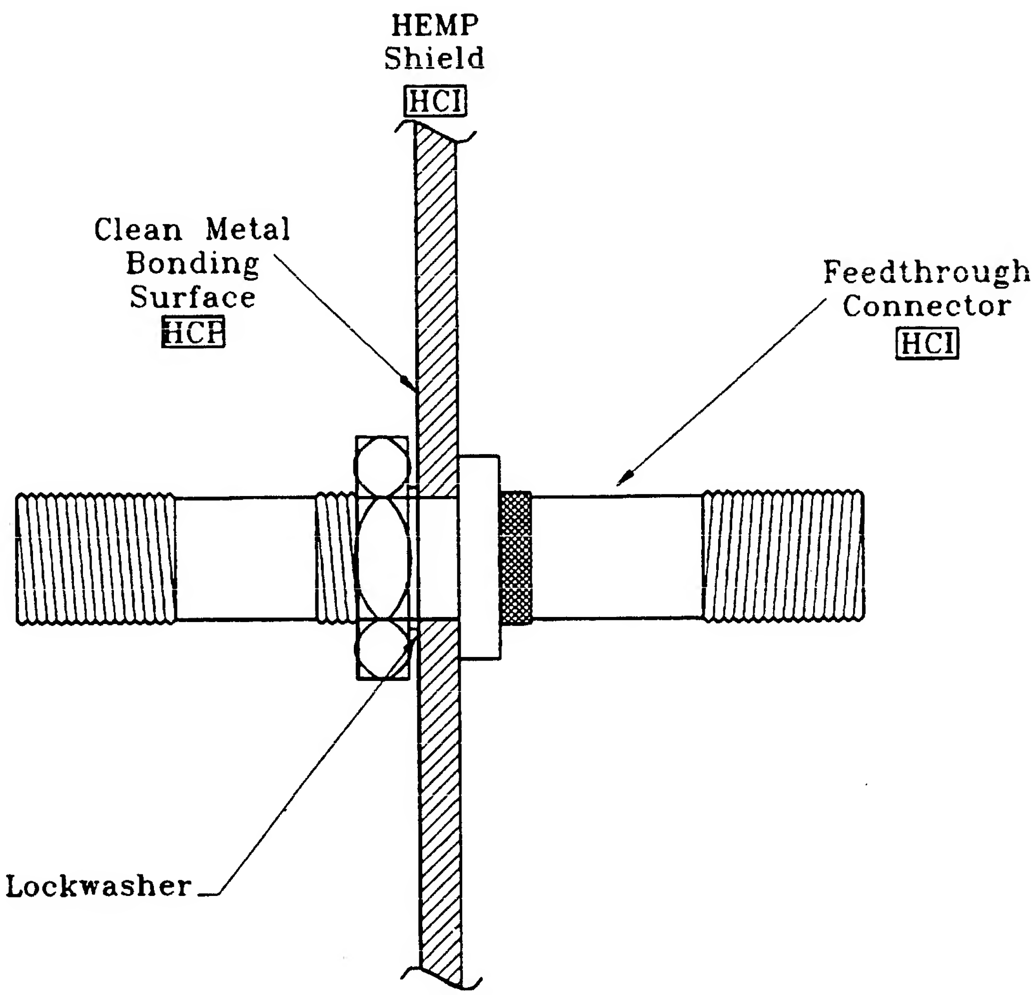


FIGURE 116. Feedthrough connector for bonding rf cable shield to shield.

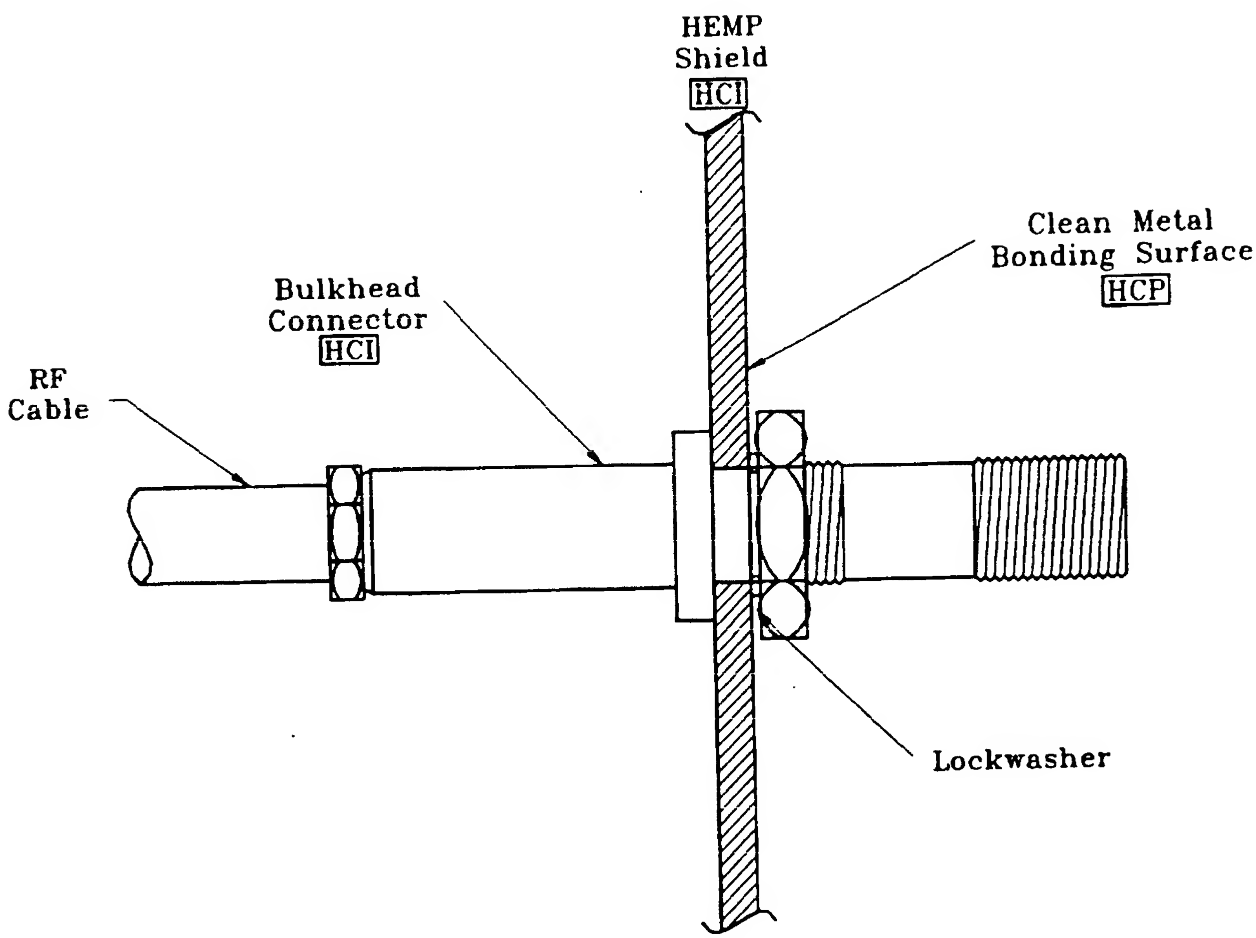


FIGURE 117. Bulkhead connector for bonding cable shield to shield.

important that the surface of the penetration entry area be clean. The connector mounting nut should be torqued against the lockwasher, so that the lockwasher bites into the mounting panel and the nut.

The rf cable penetration entry area must be protected against corrosion and contamination. The penetration entry area should at least be sheltered; it is preferred that it be in a weatherproof vault or cabinet. The bonding elements and associated cable connectors should also be protected against accidental mechanical damage by operating and maintenance personnel and by service vehicles and equipment.

The bond must have sufficiently low impedance that the short pulse current injected on the cable shield outside the facility produces a current of 0.1 A or less on the internal conductor and cable shield inside the shield. For nonburied cables, the short pulse peak current is 8 kA; for buried antenna lines, the peak current is 1 kA.

12.3.5.2.2 MF and lower frequency antenna cables. At MF and lower frequencies, resonant antenna elements are large enough that the transit time L/c, where L is the element inductance and c is the speed of light, along the element is greater than the risetime of the induced current pulse. Thus the current can build up to the full peak value; its peak value is not limited by antenna size. The specified 8 kA is approximately the short-circuit current induced in a large antenna by the HEMP. If this current is delivered to a 50 Ω cable, the voltage across the cable, the antenna terminals, and cable connectors will be 400 kV. Many connectors and terminal structures will flashover at this voltage, and some cable insulation will be overstressed.

The protection of receivers will require a combination of surge arresters and filters at the POEs to reduce the 8 kA transient to 0.1 A as required by MIL-STD-188-125. Another surge arrester at the antenna terminals is almost always necessary to protect the terminal structure, cables, and connectors against flashover. Low-pass or bandpass filters may be used to exclude the HEMP spectrum outside the passband of the radio system. In some cases, these can be integrated with the radio system tuners and couplers.

Protection elements for a receiving antenna with a balun at the antenna terminals are illustrated in figure 118. Low-capacitance, gas-tube surge arresters on both sides of the balun can be used to limit the voltages at the antenna terminals and coaxial connector to very low voltages after the gas tube fires (10-20 V). The short voltage spike that escapes through the surge arresters, before the gas tube fires, can be suppressed by a bandpass or low-pass filter between the balun and the receiver. Since there may be additional coupling to the coaxial line through the cable shield, the filter is provided with an additional gas

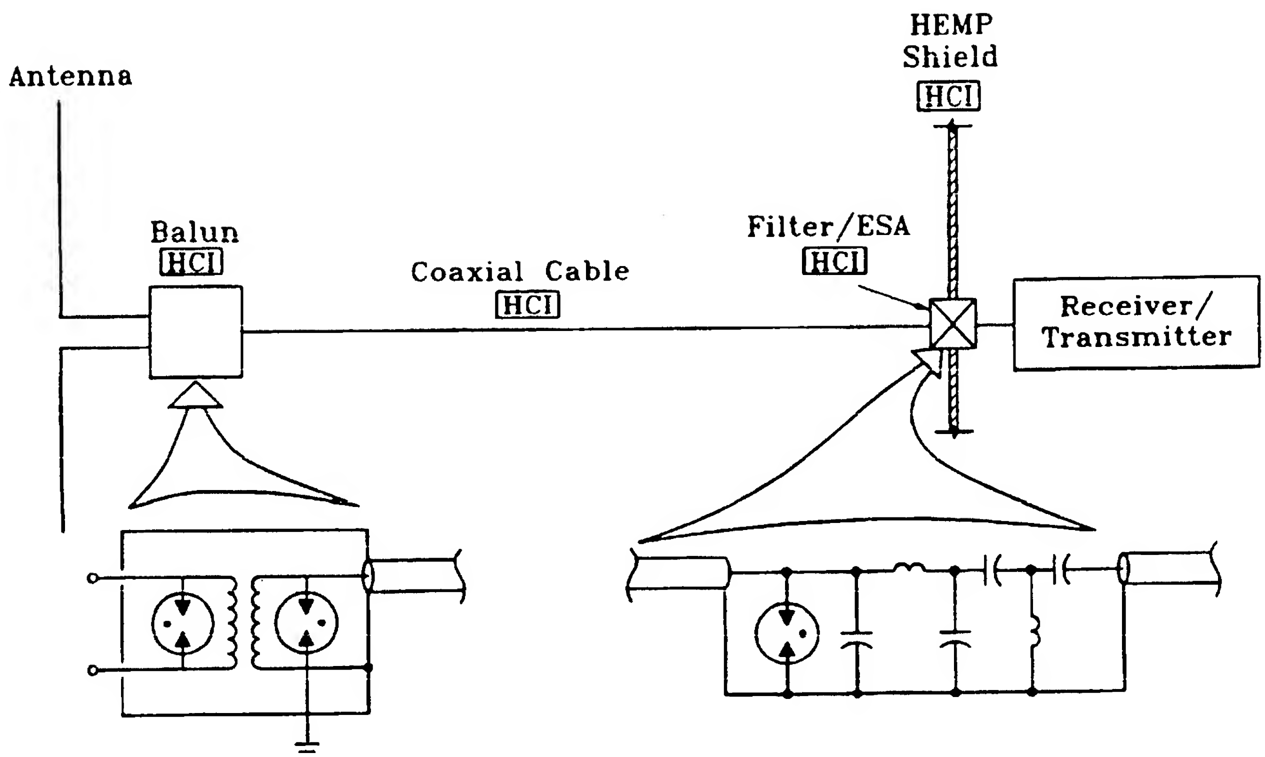


FIGURE 118. Protection elements for antenna lines operating at HF and lower.

tube surge arrester. Because the short pulse has a small impulse (charge transfer) value, relatively small gas tubes can be used on receiving antenna lines.

Antennas and cables that are used for transmitting, as well as receiving, must have more robust filters and surge arresters. Furthermore, the surge arrester firing voltage must be greater than the transmitted voltage at the surge arrester location. Table X shows the voltage and current in a 50 Ω coaxial transmission line for various transmitted power levels.

TABLE X. Peak voltage and current in a 500 coaxial cable as a fiction of the rf power.

rf Power (W)	Peak Voltage (V)	Peak Current (A)
10	31.6	0.63
100	100	2.0
1,000	316	6.3
10,000	1,000	20

Note that, for transmitter powers of 100 W or more, the surge arrester firing voltage must be several hundred volts or more. This may make it difficult to meet the requirement for a residual center conductor current of less than 1 A in high-power transmitting antenna cables. In addition, one must consider the type of transmission (e.g. amplitude or frequency modulation) in selecting the characteristic value of the surge arrester.

When it is not practical to achieve the required reduction in residual current for a transmitting antenna cable, it will be necessary to establish a special protective volume for the rf cable and transmitter. It is often the case that the transmitting system tolerates larger transient currents than the 1 A allowed by MIL-STD-188-125. When larger center conductor currents are allowed into a special protective volume, it will be necessary to assure that the current in the protected volume remains less than specified residual transient limits.

The schematic diagram in figure 118 thus applies to transmitting antenna cables as well as to receive-only cables, but the surge arrester firing voltages for transmitters should be at least twice the peak rf voltage [including a safety margin for nonoptimum voltage

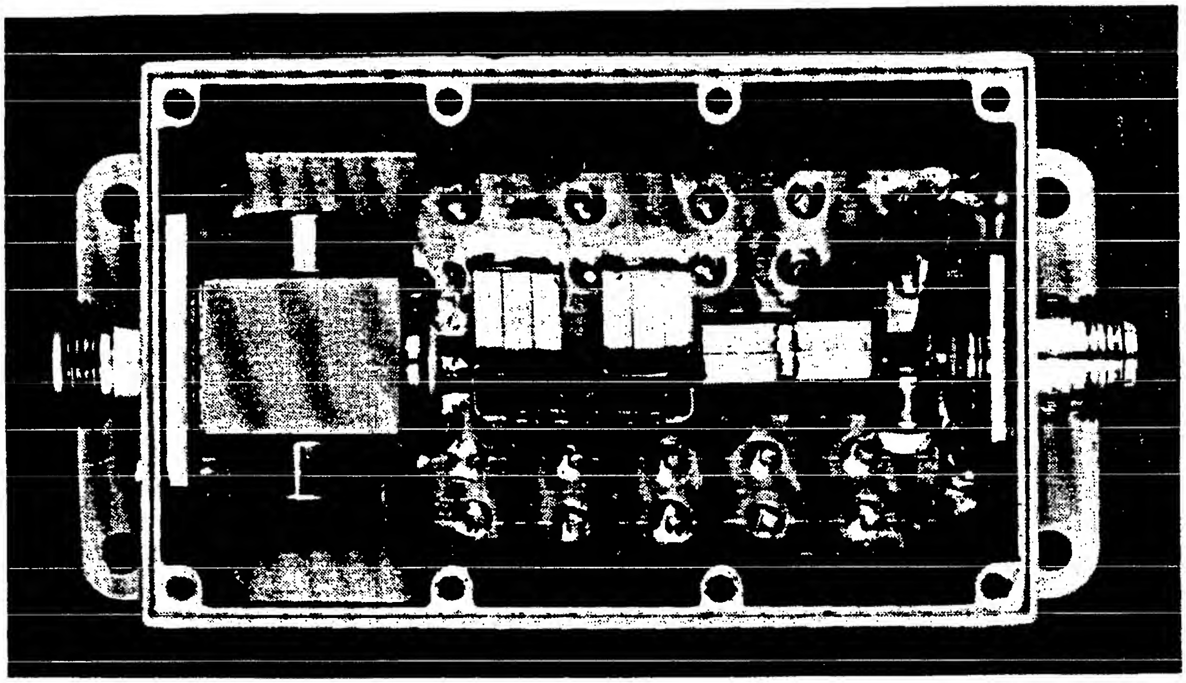
standing wave ratio (VSWR)]. The charge transfer ratings of the surge arresters should be large enough to accommodate some follow-on current, in the event the arrester fires during transmitter operation. For receive-only lines, the lowest practical gas tube voltages should be used (usually about 100 V). These may be supplemented with avalanche diodes in series with low-capacitance diodes to further reduce the transient that passes through the filter. A filter and surge arrester designed for an amplitude-modulated radio receiver is shown in figure 119. A similar filter designed for a 1-kW HF transmitter is shown in figure 120, but it should be noted that the filter elements must be more rugged in order to carry larger rf currents and tolerate the larger rf voltages. Also the transmitter unit contains only a gas tube surge arrester, while the receive-only unit contains solid state limiters on the output side.

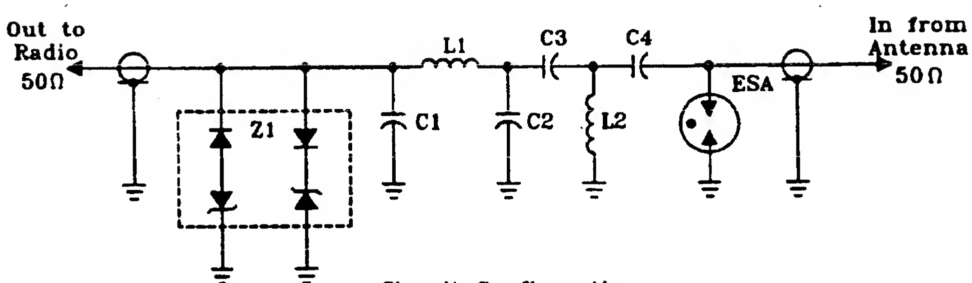
The bandpass filters shown in figures 119 and 120 can be replaced with low-pass filters for LF and lower frequency antenna cables. In addition, if the radio system operates only over a narrow portion of the band (e.g. at a fixed frequency and modulation bandwidth), it will ease the protection problem to use the narrowest filter passband that does not affect system operation.

12.3.5.2.3 **HF antenna cables.** The treatment of HF antenna lines is basically the same as that described for MF and lower frequencies. However, the stress applied to the cable is a 2 MHz damped sinusoid with 2500 A peak current, rather than the double exponential short pulse. This represents the response of a resonant HF dipole to the HEMP fields. Since the HF band is within the spectrum of the HEMP-induced stress, the primary limiting must be done with surge arresters. Low-capacitance gas tubes, supplemented with low-capacitance diodes in series with avalanche diodes, are the principal limiters available for use in HF receive-only antenna lines. The 2500 A current will produce 125 kV across a 50 Ω line.

Filters such as those in figures 119 and 120 will suppress the out-of-band HEMP-induced current spectrum, and they will limit the large rate of change in voltage and current that may be produced by gas tube surge arresters. However, much of the 2 MHz damped sinusoid will pass through the 2-30 MHz passband. When narrower operating bandwidths can be used, the HEMP filter bandwidth should be reduced accordingly.

HF transmitting antenna cables and transmitters must often be protected in special protective volumes, because of the difficulty of providing sufficient reduction in the residual HEMP transient without affecting the system performance. Fortunately, the components in HF transmitters are usually designed for large rf stresses, so that HEMP residuals greater than 1 A can often be tolerated.





Circuit Configuration

TYPE: BANDPASS FILTER

APPLICATION: BROADCAST RADIO AM RECEIVER PROTECTION

PASSBAND (FLAT): 1–1.5 MHz (3 dB)

IMAGE IMPEDANCE: 50 Ω

ATTENUATION CHARACTERISTICS:

ABOVE 1.5 MHz = 18 dB/OCTAVE, 50 dB/DECADE

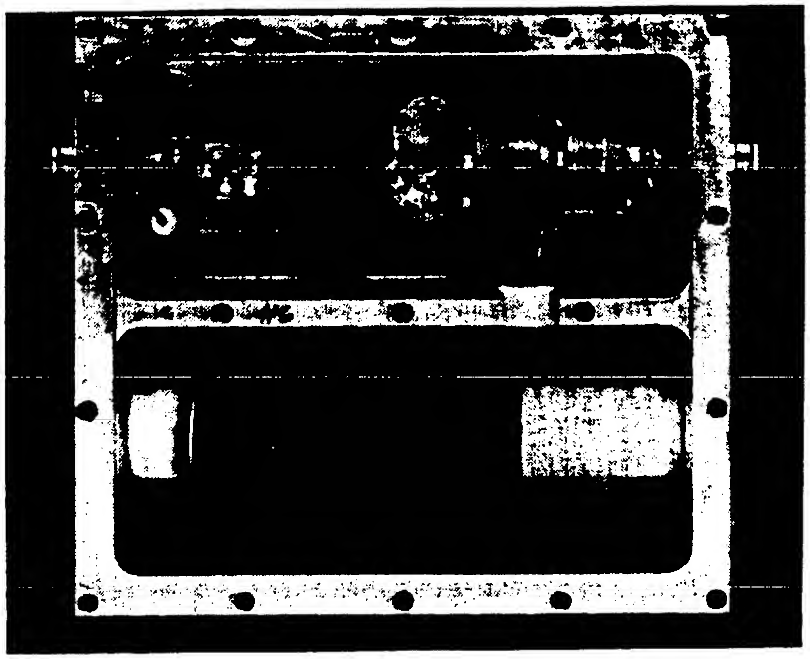
BELOW 1.0 MHz = 18 dB/OCTAVE, 60 dB/DECADE

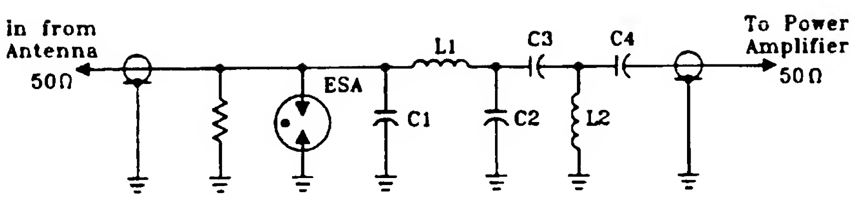
CONNECTORS: TYPE "N"

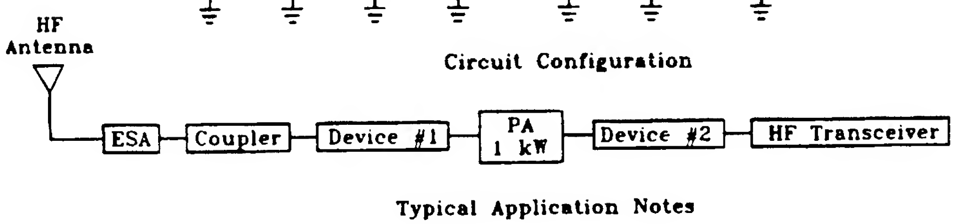
SIZE: 13.3 cm L × 6.6 cm W × 4.8 cm H

WEIGHT: 453 g

FIGURE 119. MF radio receiver HEMP protection device (reference 12-8).







TYPE: HIGH FREQUENCY BANDPASS FILTER No. 1

APPLICATION: HF POWER AMPLIFIER OUTPUT

POWER HANDLING CAPACITY: 1 kW (cw)

PASSBAND (FLAT): 1.6–30 MHz

IMAGE IMPEDANCE: 50 Ω

ATTENUATION CHARACTERISTICS:

INBAND INSERTION LOSS: <1 dB

EMP PROTECTION: 80 dB TYPICAL

CONNECTORS: TYPE "N"

SIZE: 17.8 cm L × 14 cm W × 7.6 cm H

WEIGHT: 1.1 kg

FIGURE 120. One kilowatt HF transceiver HEMP protection device (reference 12-8).

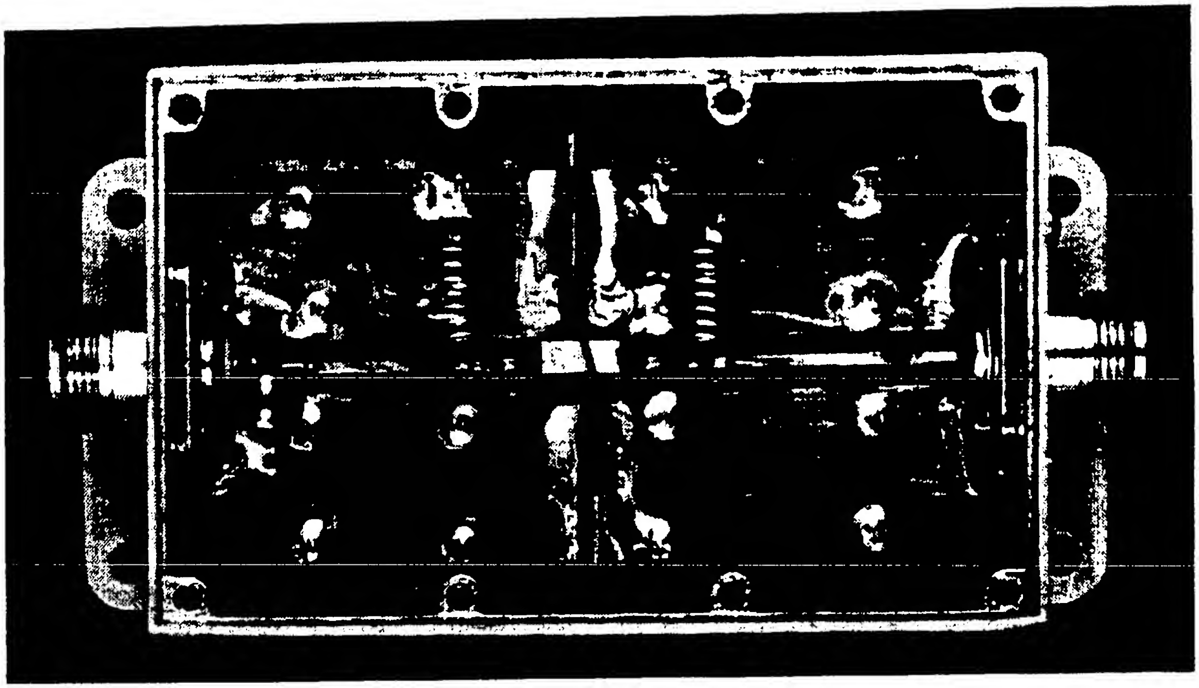
For HF and higher frequencies, it is well to be aware of the potential for intermodulation of two or more signals in the nonlinear surge arresters. Nonlinear devices should not be activated by received signals, and a linear filter should be placed between the nonlinear devices and interior electronics to act as a buffer. In addition, gas tubes exhibit negative dynamic resistance when they fire, since the current increases as the voltage decreases. This negative dynamic resistance occasionally produces unstable circuit responses, if the system positive resistance is comparable to the negative dynamic resistance.

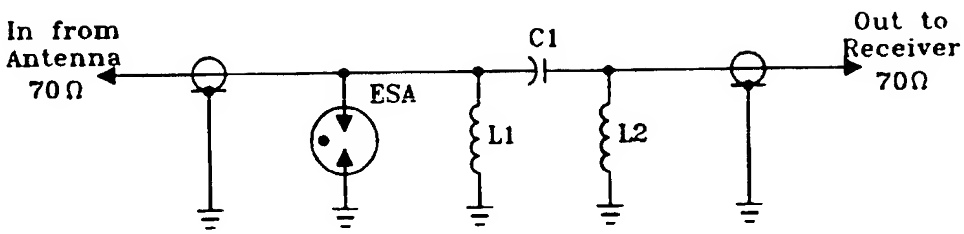
12.3.5.2.4 VHF antenna cables. The very high frequency (VHF) band, 30-200 MHz, is in that portion of the HEMP spectrum where the energy density is decreasing with frequency. The HEMP excitation of the largest resonant antennas in this band will produce a 30 MHz damped sinusoid with a short circuit current of about 900 A. This transient will produce 45 kV peak voltage across a 50 Ω cable.

Protection techniques applicable to VHF cables are similar to those described for lower frequencies. However, greater attention to the control of lead inductance and stray capacitance is necessary at VHF frequencies. A capacitive reactance of 500 Ω (10 times the impedance of 50 Ω cables) requires only 10 pF at 30 MHz and 1.6 pF at 200 MHz. Thus, only very low capacitance gas tubes can be used as surge arresters at VHF frequencies. Similarly the lead inductance required to produce a 5 Ω reactance (10 percent of the line impedance) is 26 nH at 30 MHz and only 4 nH at 200 MHz [the inductance of 2.5 cm (1 in) of wire is about 26 nH].

To protect the antenna terminals and cable connectors against the 45 kV damped sinusoid, a low-capacitance, leadless surge arrester should be placed at (or within a few centimeters of) the antenna terminals. A coaxial surge arrester with low insertion loss is desirable. The firing voltage of the surge arrester should be at least two times the operating voltages in transmitting antenna cables.

Bandpass filters can also be used to suppress out-of-band HEMP induced currents. A filter designed for a television receiving antenna cable is illustrated in figure 121. Note that the line impedance is preserved inside the filter box by the use of a strip line between the input and output connectors. Also note the very short leads on the small gas tube surge arrester near the input connector. Narrowband systems operating near the upper frequency in this band may use filters constructed from transmission line stubs, rather than lumped elements. For example, a quarterwave shorted stub across the line is an open circuit at the quarterwave resonance frequency, but it is a very low impedance (nearly a short) to frequencies in the HEMP spectrum well below the resonance frequency [see also ultrahigh frequency (UHF) antenna cables]. The quarterwave stub can also be made rugged enough to tolerate lightning transients.





Circuit Configuration

TYPE: HIGH PASS FILTER

APPLICATION: FM AND VHF TV RECEIVER PROTECTION

PASSBAND (FLAT): 88–220 MHz (3 dB)

CUTOFF FREQUENCY (F_{CO}): 88 MHz

IMAGE IMPEDANCE: 70 Ω

VSWR 220 MHz ≤ 1.5:1

ATTENUATION CHARACTERISTICS:
BELOW 88 MHz = 18 dB/OCTAVE, 60 dB/DECADE
EMP THREAT = 30 VPP MAX

CONNECTORS: TYPE "N" (70 Ω)

SIZE: 13.3 cm L × 6.6 cm W × 4.8 cm H

WEIGHT: 453 g

FIGURE 121. VHF television receiver HEMP protection device (reference 12–8).

12.3.5.2.5 UHF antenna cables. For systems operating at UHF and higher frequencies, the specified HEMP stress is a 200 MHz damped sinusoidal current with a peak of 250 A. This current produces 12.5 kV peak voltage across a 50 Ω antenna feed cable. This voltage can break down connectors and antenna terminals.

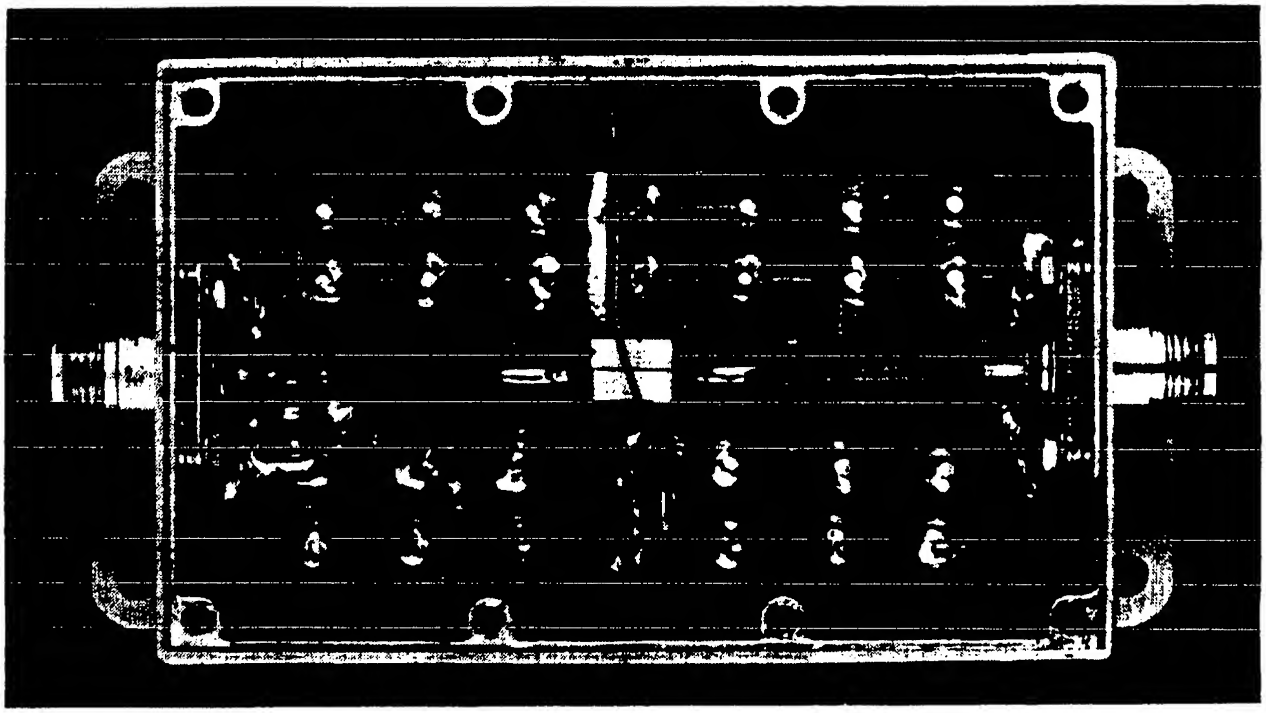
The protection approach for UHF is based on the same concept that has been described for lower frequencies. Surge arresters are used to limit the line voltage, and filters are used to suppress out-of-band responses. At UHF, coaxial surge arresters with low insertion loss are preferred, because even a few picofarads of stray capacitance can produce undesired reflections with an accompanying increase in the voltage standing wave ratio. Filters in this band tend to be constructed from transmission line segments combined with lumped elements, rather than lumped elements alone. Figure 122 shows a bandpass filter with surge arrester for a television receive-only antenna line. Note that the inductors are 3-turn coils placed at selected positions along a strip line. In the high UHF band, high-pass filters may be used, since the HEMP spectrum falls off exponentially in the gigahertz range.

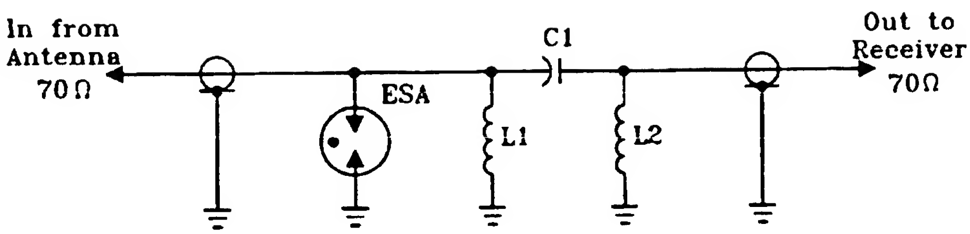
Figure 123 illustrates the use of a coaxial surge arrester to protect the cable connector and a quarterwave short stub to act as a bandpass filter. A high-pass filter at the HEMP shield suppresses the part of the HEMP response spectrum below the UHF band. In the upper VHF and UHF bands, considerable skill is required to design filters with a low voltage standing wave ratio in the operating band and a large insertion loss at frequencies outside the operating band.

12.3.6 HEMP protection using conduit shielding.

12.3.6.1 MIL-STD-188-125 requirements for conduit shielding.

> 5.1.7.9 Conduit shielding.
>
> 5.1.7.9.1 Buried control and signal line conduits. A control and signal cable run between two protected volumes may be HEMP-protected using a buried metal conduit, when the length of the run is less than 25 m (82 ft). A cable containing one (or more) control or signal lines or one (or more) power lines with maximum operating current below 1.0 A is considered to be a control and signal cable. A conduit is considered buried when less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill. Transient suppression/attenuation devices are not required on the penetrating conductors under these conditions.





Circuit Configuration

TYPE: UHF HIGH PASS FILTER

APPLICATION: UHF TV RECEIVER PROTECTION

PASSBAND (FLAT): 400–900 MHz

CUTOFF FREQUENCY (F_{CO}): 400 MHz

IMAGE IMPEDANCE: 70 Ω

ATTENUATION CHARACTERISTICS:
BELOW 400 MHz = 18 dB/OCTAVE.
60 dB/DECADE
EMP THREAT = 30 VPP MAX

CONNECTORS: TYPE "N" (70 Ω)

SIZE: 13.3 cm L × 6.6 cm W × 4.8 cm H

WEIGHT: 453 g

FIGURE 122. UHF receiver HEMP protection device (reference 12-8).

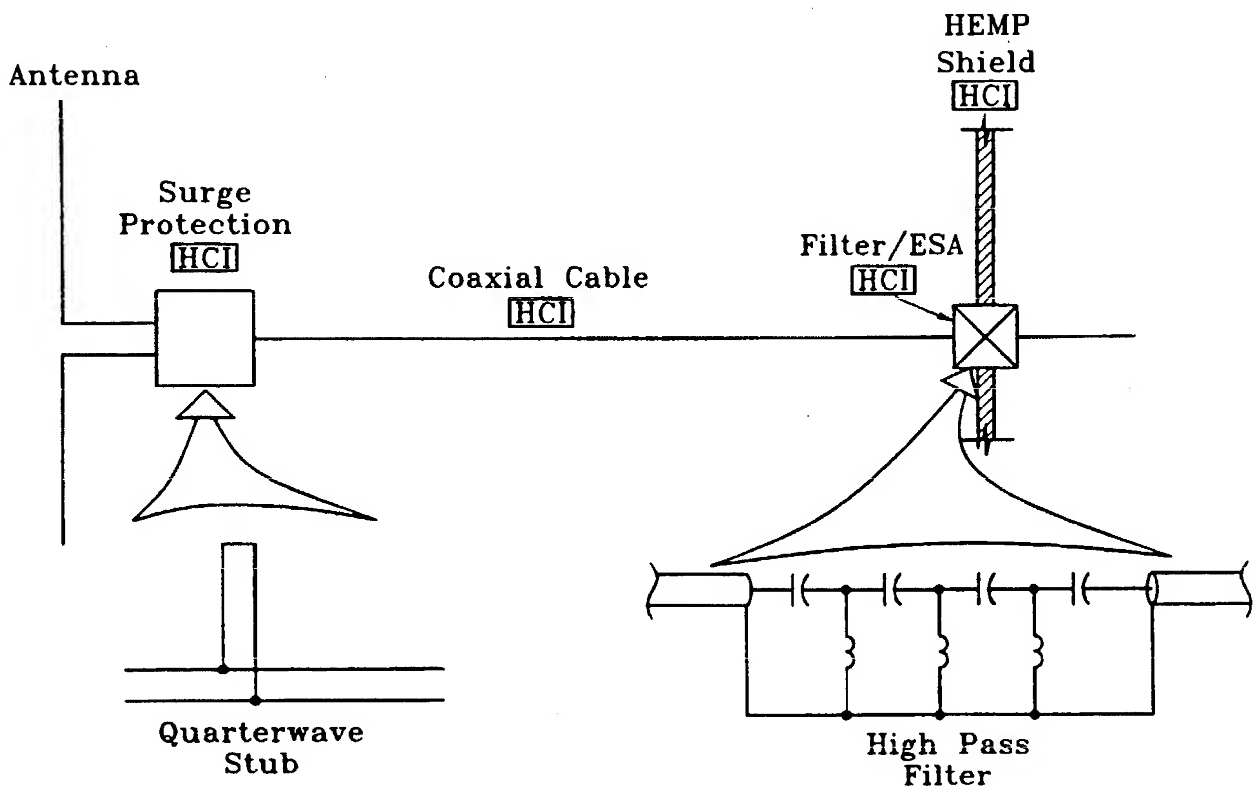


FIGURE 123. UHF antenna line protection.

5.1.7.9.2 Nonburied control and signal line conduits. A control and signal cable run between two protected volumes may be HEMP-protected using a nonburied metal conduit when the length of the run is less than 3.1 m (10.2 ft). A conduit is considered nonburied when 1 m (9.9 ft) or more of its total length is not covered by earth or concrete fill. Transient suppression/attenuation devices are not required on the penetrating conductors under these conditions.

5.1.7.9.3 Power line conduits. A cable run between two protected volumes and containing only power lines with operating currents above 10 A may be HEMP-protected using a buried metal conduit, when the length of the run is less than 2500 m (8200 ft). A cable run between two protected volumes and containing only power lines with operating currents above 10 A may be HEMP-protected using a nonburied metal conduit, when the length of the run is less than 312 m (1025 ft). For a cable run of power lines with operating currents between 1.0 A and 10 A, the maximum conduit length is 250 m (820 ft) for a buried conduit and 31.2 m (102 ft) for a non buried conduit. Transient suppression/attenuation devices are not required on the penetrating conductors under these conditions.

5.1.7.9.4 Conduit requirements. HEMP protection conduits shall be rigid metal conduit, circumferentially welded or brazed at all joints and couplings, and circumferentially welded or brazed to the facility HEMP shields at POEs on both ends. Pull boxes in the conduit run shall be welded or brazed metal enclosures and shall be electromagnetically closed with welded, brazed, or radio frequency gasketed and bolted covers. A 1000 A pulse on a buried control and signal line conduit and an 8000 A pulse on a non buried control and signal line conduit, with 10 ns risetime and 500 ns FWHM, shall produce a residual internal transient stress no greater than 0.1 A on the wire bundle inside the conduit.[4] The same pulses occurring on the outer surface of a power line conduit shall produce a residual internal transient stress no greater than 10 A, when the operating current on the lowest rated conductor in the wire bundle inside the conduit is above 10 A, and no greater than 1.0 A when the operating current is between 1.0 A and 10 A.[4]

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[4] Common mode pulse withstanding requirements, waveform details of the injected pulses, additional constraints on the residual internal transient stress, and circuit test configuration information are contained in PCI test procedures of appendix B.

12.3.6.2 Conduit protection methods. Under conditions specified in MIL-STD-188-125, conduit shielding of wiring can be used for HEMP protection instead of transient suppression/attenuation devices at electrical POEs. The first of these conditions is that

the circuits at both ends of the conduit must be enclosed within MIL-STD-188-125 electromagnetic barriers. This requirement ensures that the wiring will not be driven significantly by HEMP coupling to the terminations.

The second condition is a set of restrictions on the length of the conduit. The maximum length varies with the electrical class (control and signal or power), with the normal operating current (power lines only), and whether the conduit is aboveground or buried. These length restrictions ensure that the HEMP-induced transients on the protected wiring due to diffusion through the conduit will not exceed the residual internal stress limits for the protected volume.

The conduit construction and installation requirements constitute the third and final condition. The following hardness critical items and processes must be used:

a. The conduit must be rigid metal conduit.

b. Solid-metal walled, bellows-type conduit must be used if provisions for expansion and contraction are required; braided flexible conduit may not be used.

c. Circumferential welding is required at all joints and couplings; threaded connections are not adequate unless subsequently welded.

d. The conduit must be circumferentially welded to the HEMP shields at both ends.

e. Pull boxes in the conduit run must be electromagnetic closed with high-quality rf seals.

Unless all of these conditions are satisfied, filters and ESAs are required at the barrier POEs on both ends.

Conduit protection should also be used for HEMP protection of other mission-critical wiring outside the HEMP barrier. The same practices described above apply to these applications.

12.3.7 Penetration entry area.

12.3.7.1 MIL-STD-188-125 requirements for the penetration entry area. The penetration entry area is defined by MIL-STD-188-125 as follows:

> 3.3.15 Penetration entry area. The penetration entry area is that area of the electromagnetic barrier where long penetrating conductors (such as an electrical power feeder) and piping points-of-entry are to be concentrated.

It is a portion of the shield, often thicker than the rest of the shield, that is carefully controlled to eliminate any seams, apertures, or cracks that might be excited by the large currents diverted to the shield from the external conductors. In addition, MIL-STD-188-125 states:

> 5.1.1.2 Penetration entry area. As design objective, there should be a single penetration entry area on the electromagnetic barrier for all piping and electrical POEs except those connected to external conductors less than 10 m (32.8 ft) in length. The penetration entry area shall be located as far from normal and emergency personnel and equipment accesses and ventilation POEs as is permitted by the facility floor plan.

A single penetration area is desired to avoid the possibility of large currents flowing across the shield. High-frequency currents flowing over the shield as illustrated in figure 124 excite doors, entryways, and any flaws that might develop in the shield. Low-frequency currents can diffuse through the shield and flow through internal structures and circuits. This is one reason it is desirable to block the late-time currents rather than try to divert them.

12.3.7.2 Penetration entry area design. With a single penetration entry area, as illustrated in figure 125, the external conductor currents all enter and exit in the same controlled area. The remainder of the shield is not strongly excited by the currents deposited on the entry area shield surface. Since short external conductors do not have large currents induced on them, it is less important that they all be attached at the single entry area. MIL-STD-188-125 thus excludes external conductors less than 10 m long from its single entry area objective.

A schematic of a penetration entry area is shown in figure 126. The entry area is a controlled and accessible portion of the shield wall where all of the pipe, waveguides, and coaxial cable shields are bonded to the facility shield as they enter the facility. The commercial power line and other electrical penetrations also enter through the penetration

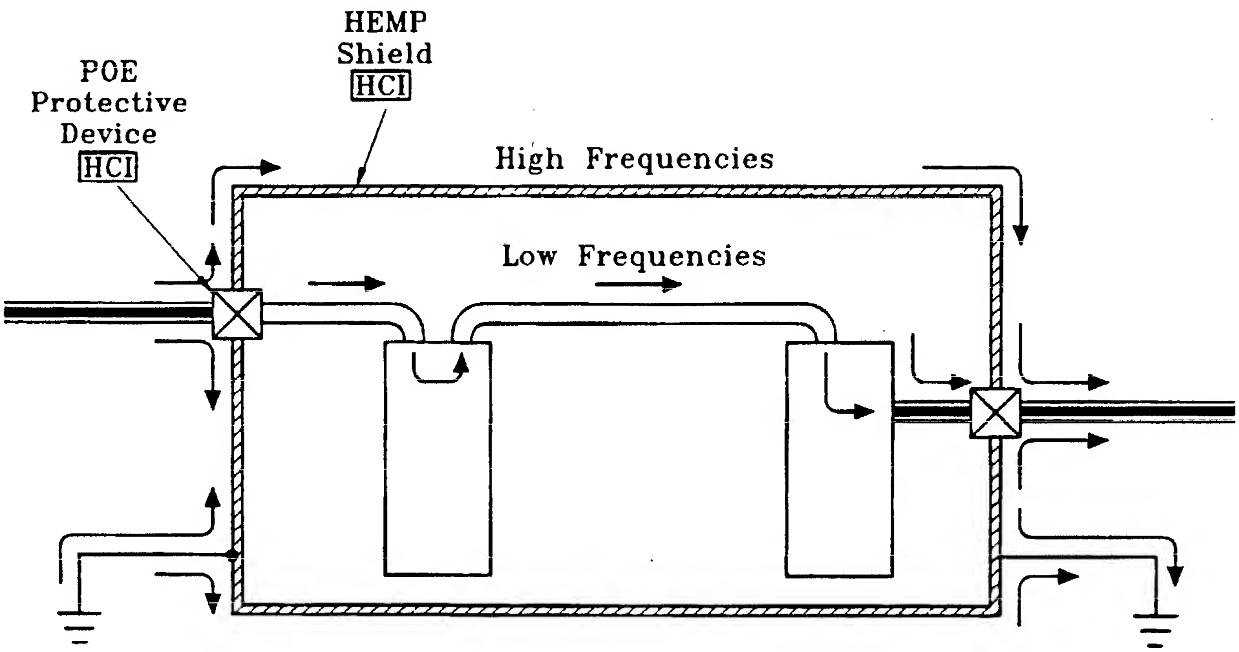

FIGURE 124. Shield and internal equipment excitation by external conductor currents.

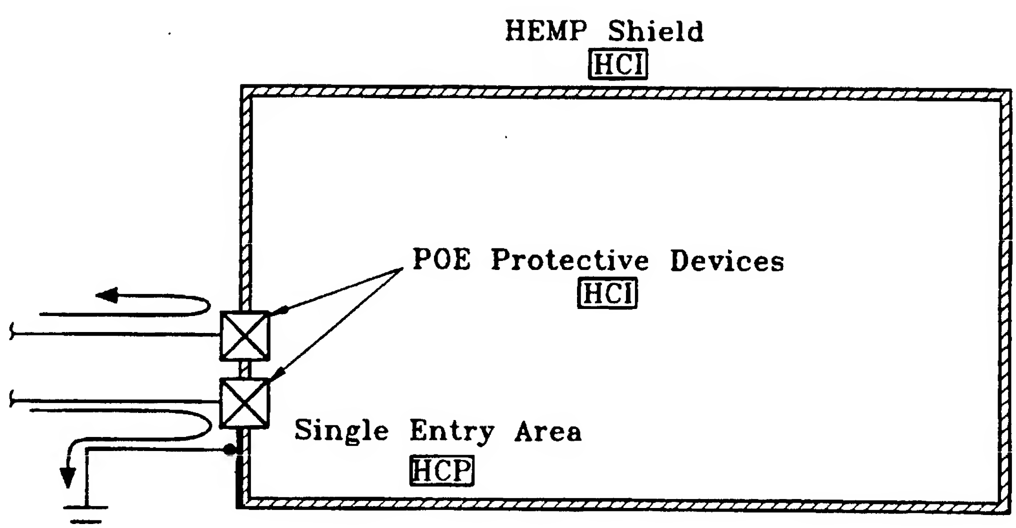

FIGURE 125. Use of single entry area to minimize external excitation of facility HEMP shield.

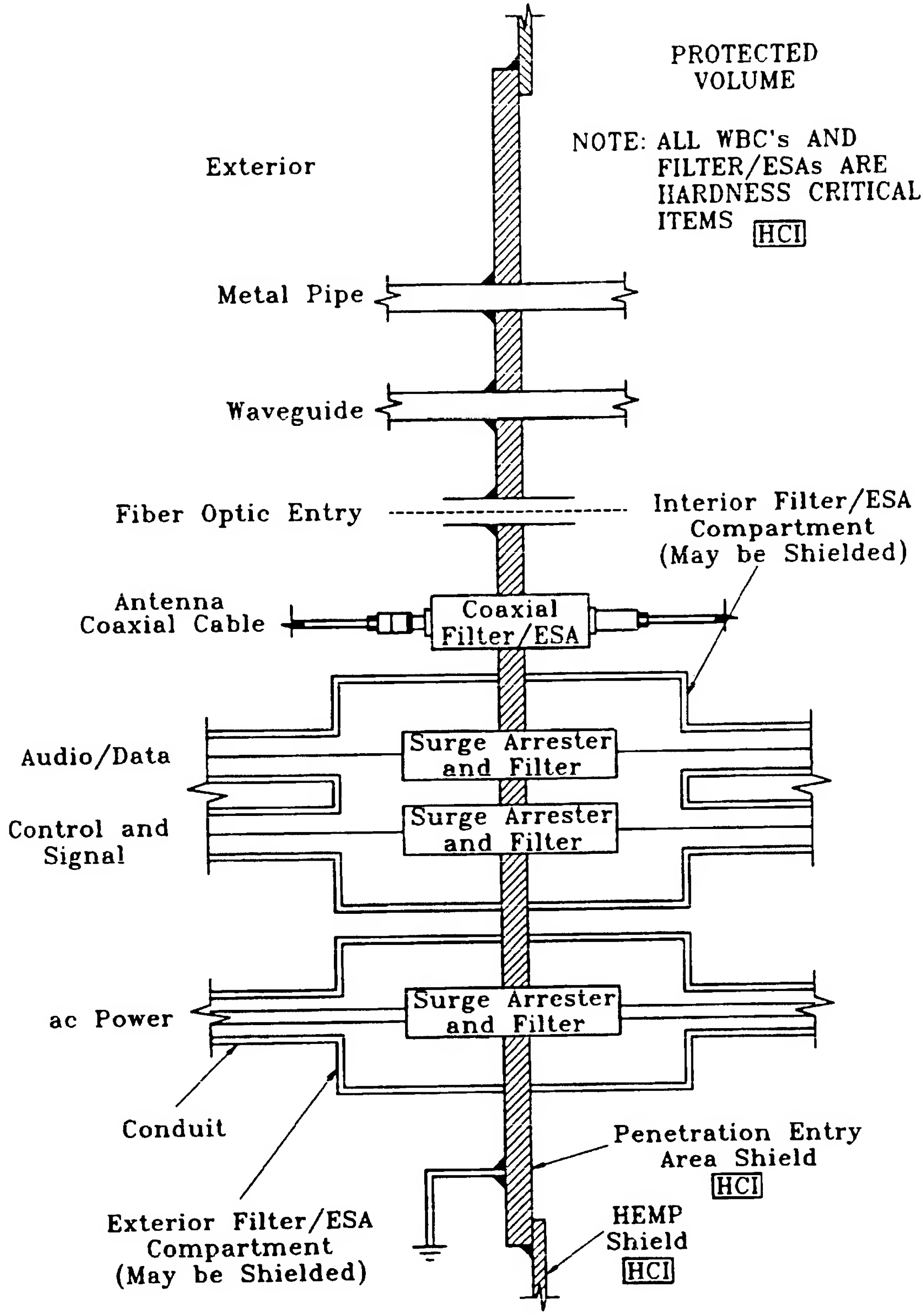

FIGURE 126. Schematic diagram of penetration entry area.

entry area. The PEA shield is often made of somewhat thicker material than the remainder of the shield. The added thickness is primarily for mechanical strength, but it also acts to provide extra shielding in this area where large external currents are deposited.

The filter/ESA enclosures or cabinets, which house the filters and surge arresters, are usually mounted on and attached to the PEA shield wall. These housings provide physical and environmental protection for the components. They also prevent operators and maintenance personnel from accidentally coming in contact with the exposed, energized terminals of the devices. The imbedded form of filter enclosure is required for primary barrier POEs. This configuration is schematically illustrated in figure 126, and it is shown in greater detail in MIL-STD-188-125.

The exterior and interior compartments of an imbedded filter/ESA enclosure are not required to be shielded as part of the primary HEMP barrier. However, shielding may be specified if the compartment surfaces are part of the topology of a special protective barrier. Shielded compartments may also be employed to prevent mutual interference between high-level HEMP and operating signals on power lines and small signals on the audio/data and control/signal conductors.

Other configurations for filter/ESA enclosures are shown in figures 127, 128, and 129. These may be used in HEMP shields that are installed as special protective measures and for other applications. The reentrant and protruding forms in figures 127 and 128 sometimes provide more convenient access to the components for test and maintenance. Note that the small series inductance used to ensure surge arrester activation for capacitive input filters can be obtained by specifying the length of the wiring from the ESA to the filter.

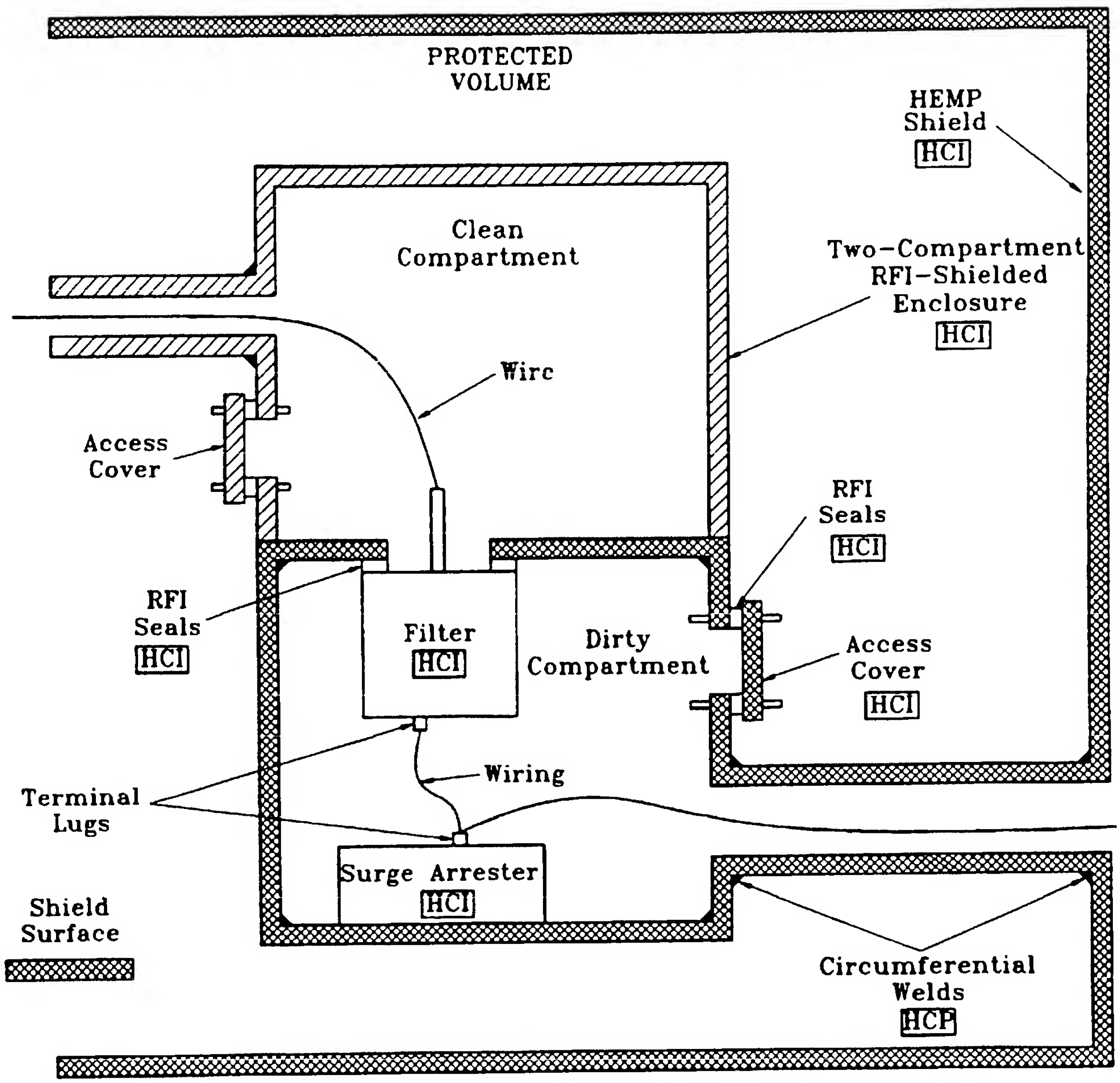

FIGURE 127. Reentrant filter compartment.

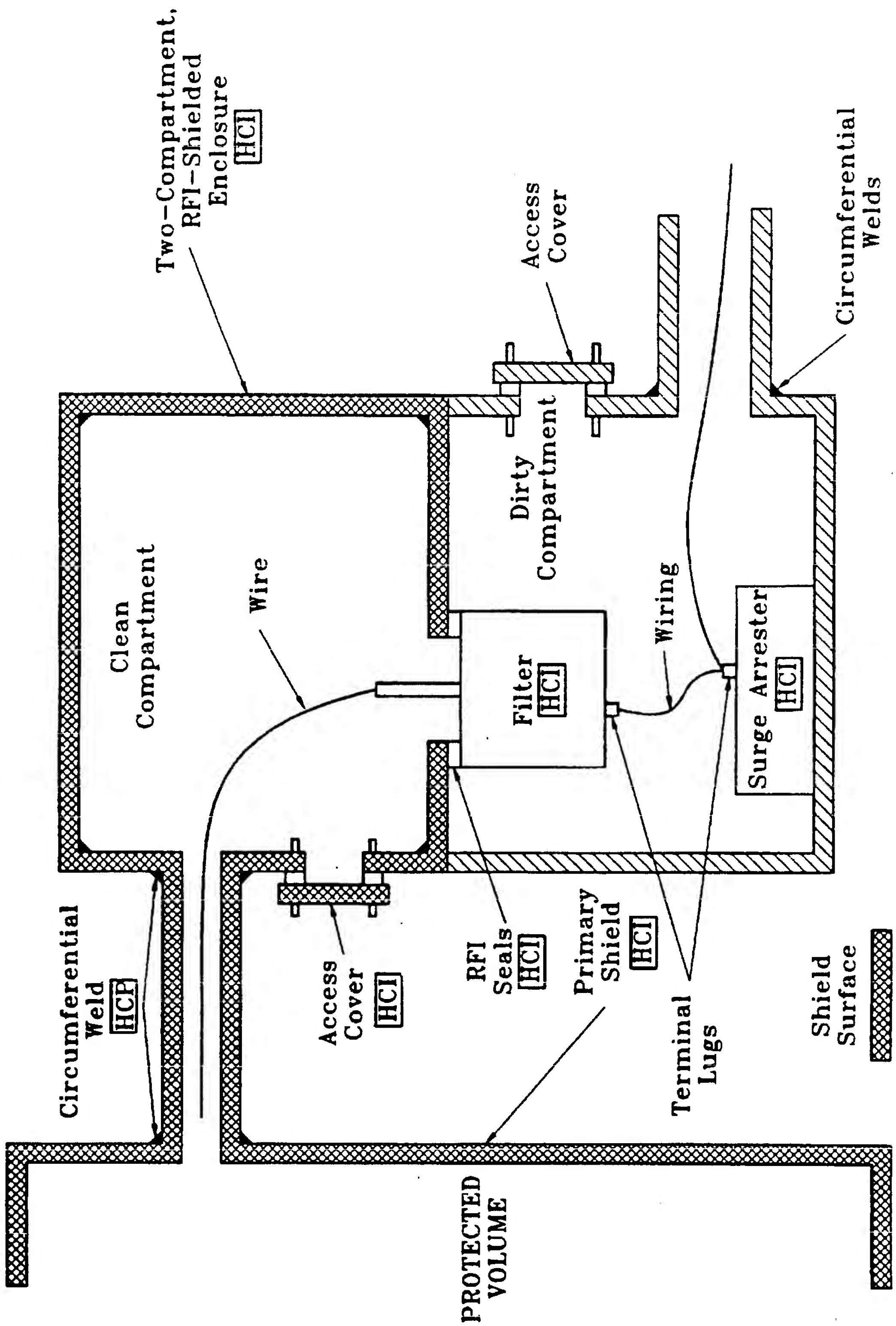

FIGURE 128. Protruding filter compartment.

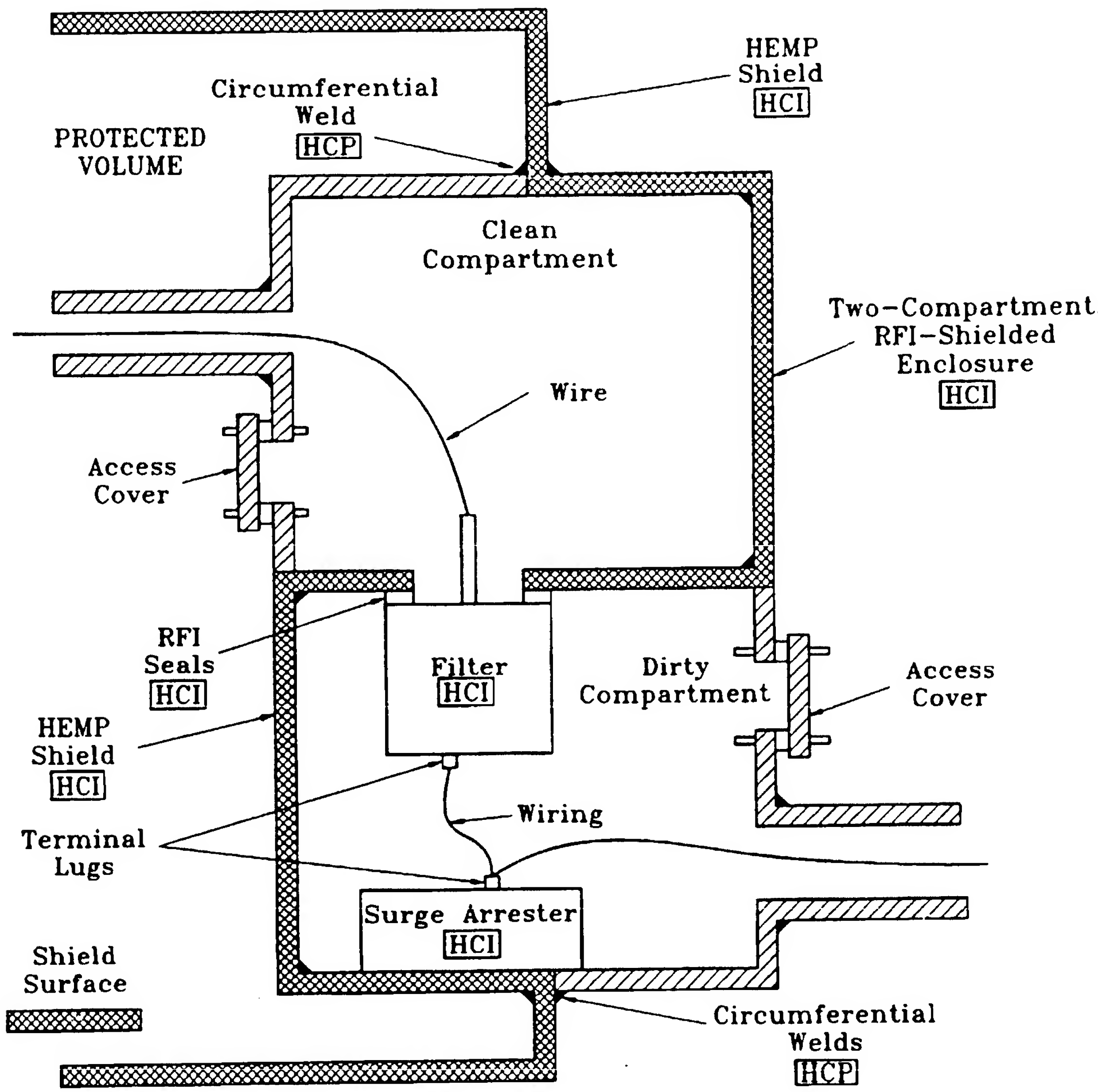

FIGURE 129. Filter and surge arrester compartment in penetration entry area.

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13. GROUNDING AND BONDING

13.1 Basic principles. The ground system in an unhardened, fixed, ground-based facility serves three principal functions. These functions as defined in MIL-STD-188-124 (reference 13–1) and MIL-HDBK-419 (reference 13–2) are personnel safety, equipment and facility protection, and electrical noise reduction.

Bonding refers to the process by which a low-impedance path for the flow of an electrical current is established between two metal objects. In the context of this section, the discussion of bonds is limited to bonds associated with grounding between metal objects intended to be at ground potential.

Grounding and bonding at military ground-based CI facilities is performed in accordance with requirements of MIL-STD-188-124 and supplementary guidance in MIL-HDBK-419. Additionally, these facilities must comply with several related commercial/industrial codes and standards. ANSI/NFPA 70, "National Electrical Code" (reference 13–3), establishes installation requirements for the electrical fault protection subsystem. ANSI/NFPA 78, "Lightning Protection Code" (reference 13-4), prescribes the requirements for lightning protection of buildings and structures.

Additional grounding and bonding requirements apply to facilities that process national security information. These requirements are contained in MIL-HDBK-232 (reference 13–5) and various other publications of the National Security Agency and the military departments.

A vast assortment of conductors must be joined or bonded together to provide a low-impedance grounding network and to achieve an effective ground system. These conductors include metal structures, equipment racks and chassis, cable trays and conduits, pipes, and many other metallic objects.

The same three functions discussed above are accomplished by grounding and bonding at a HEMP-hardened facility. The ground system also provides the path for conducting HEMP-induced transients to ground. The HEMP electromagnetic barrier required by MIL-STD-188-125 (reference 13-6) will not compromise any of the conventional functions of the ground system. Similarly, the ground system will not compromise the HEMP protection if the requirements of MIL-STD-188-125 and guidelines in this section are observed.

The references listed at the end of this section describe normal grounding and bonding requirements and practices in great detail, and it is inappropriate for this handbook to

reiterate this information. This section will, however, discuss those grounding and bonding treatments that have a direct effect on the HEMP protection of the facility.

13.2 MIL-STD-188-125 requirements.

> 5.1.2 Facility grounding.
>
> 5.1.2.1 Equipotential ground plane. Fixed ground-based C⁴I facilities shall be grounded using the equipotential ground plane method in accordance with MIL-STD-188-124 and guidance in MIL-HDBK-419. The facility HEMP shield shall form a major portion of the equipotential ground plane.
>
> 5.1.2.2 Grounding to the facility HEMP shield. Grounds for equipment and structures enclosed within the protected volume shall be electrically bonded to the inside surface of the shield by the shortest practical paths, including via the raised floor structure. Grounds for equipment and structures outside the electromagnetic barrier shall be electrically bonded to the outside surface of the shield or to the earth electrode subsystem. Ground cables used to connect the facility shield (equipotential ground plane) to the earth electrode subsystem shall be electrically bonded to the outside surface of the shield, and at least one such ground cable shall be located at the penetration entry area. All grounding connections to the facility HEMP shield shall be made in a manner which does not create POEs.

13.3 Applications.

13.3.1 Grounding. The requirements of MIL-STD-188-125 address the two most important interactions between the HEMP barrier and the ground system. These are:

a. The shield will serve as the equipotential ground plane and will be electrically bonded to the earth electrode subsystem.

b. Grounding conductors are not to penetrate the HEMP barrier.

An equipotential plane (also defined in section 3) is "a mass, or masses, of conducting material which, when bonded together, offers a negligible impedance to current flow." It is evident that the HEMP shield, which is a massive sheet of conductive material that surrounds the protected volume, is ideal for this purpose. Use of the HEMP shield as the equipotential plane also removes any reason for grounding conductors to penetrate the HEMP shield. Both of these concepts are illustrated in figures 130 and 131. To highlight

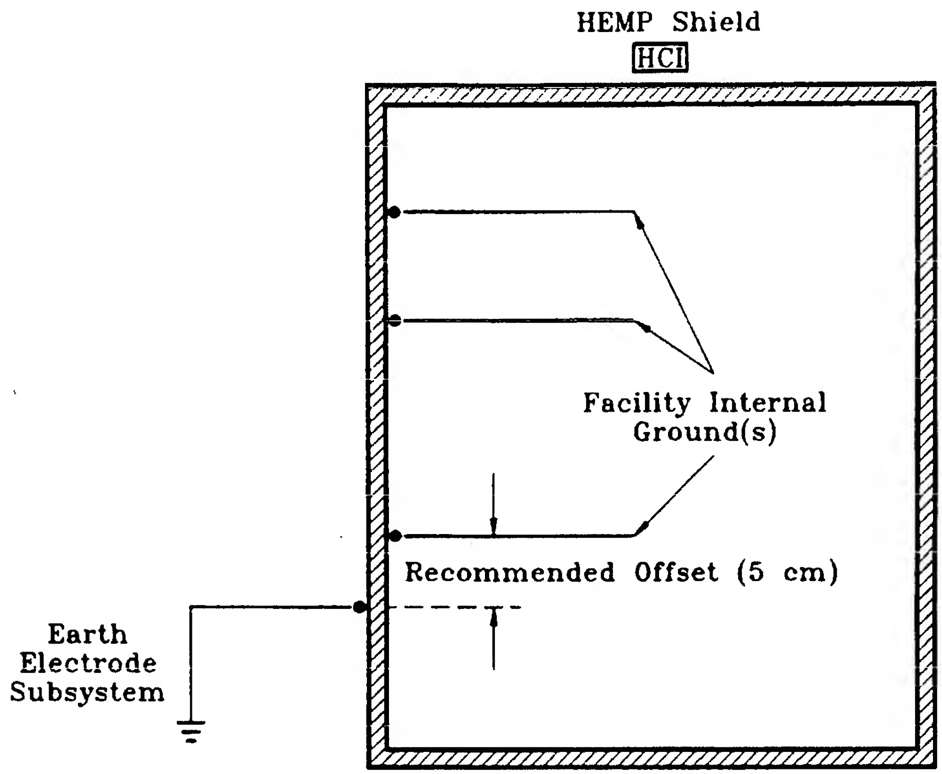

FIGURE 130. Proper bonding of ground conductor to shield.

the requirement for eliminating ground wire POEs, it is recommended that external ground connections to the shield be offset from internal attachment points by at least 5 cm.

An important function of the HEMP barrier is to serve as a 'dump" to ground for the large HEMP-induced current transients that are propagated to the barrier on long lines. It is not desirable to allow HEMP-induced currents to flow through or over the HEMP shield to reach a ground. When the HEMP barrier is bonded to the earth electrode subsystem at many points, the connections should be arranged so that large HEMP currents will not be forced to flow across the shield and across apertures such as WBCs or doors. This is a major reason for the penetration entry area discussed in sections 6 and 12. The external current collectors nearly all connect to the HEMP barrier at that common area, and the PEA must be well-grounded with a very low-impedance path to the earth electrode subsystem.

The earth electrode subsystem described in MIL-HDBK-419 is designed to provide a maximum dc resistance to ground of 10 Ω . This is achieved by a ring ground of periodically spaced ground rods, whose number and length are determined by the soil resistivity.

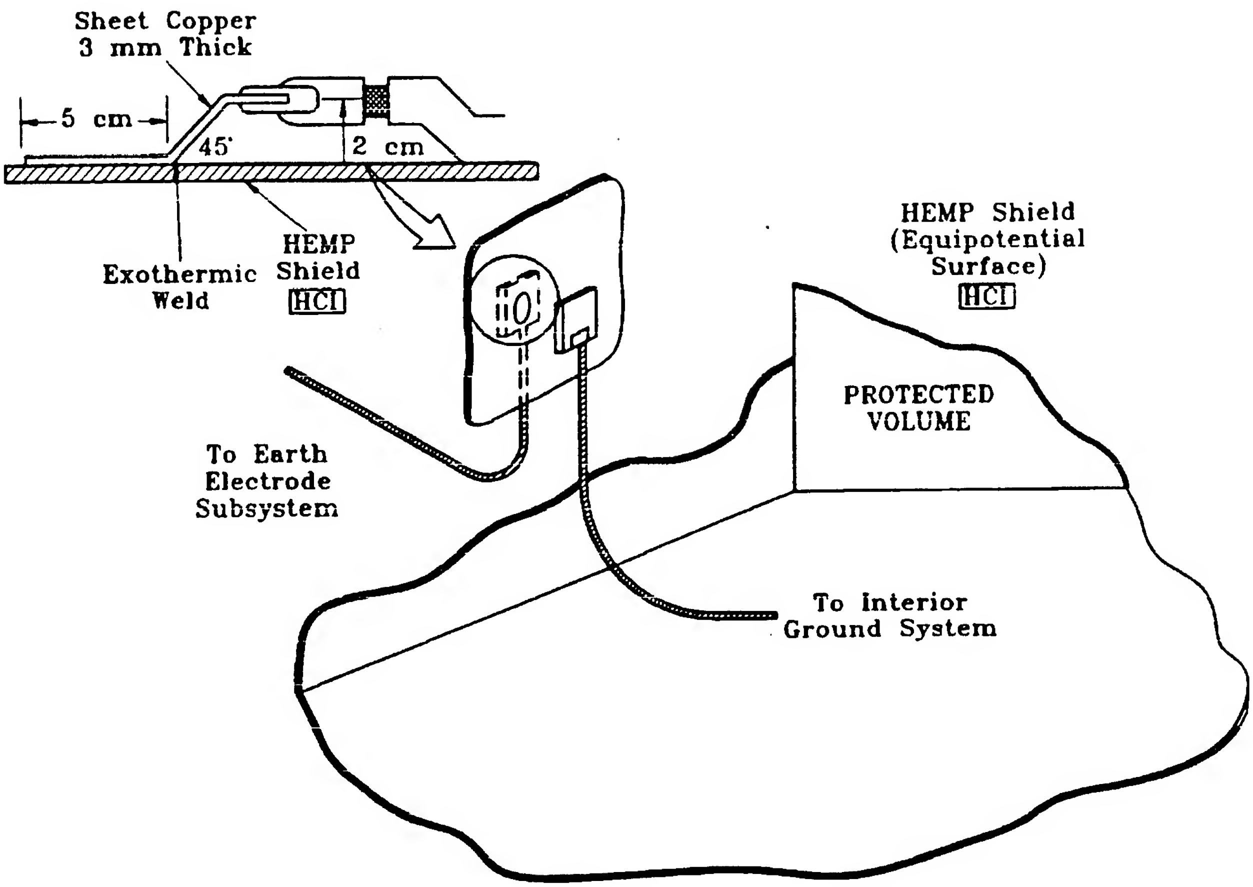

FIGURE 131. Grounding interface with the HEMP shield.

Where bedrock or other obstacles prevent the effective use of vertical ground rods, horizontal conducting wire grids or radials should be used. Where horizontal conductors are not effective, lowering the soil resistivity through chemical enhancement (salting) may be necessary. In this case, MIL-HDBK-419 should be consulted.

An internal electrical fault protection subsystem is provided to protect personnel and equipment from power fault currents and static charge buildup. The ac power neutral is grounded at one point, usually at the first commercial power service disconnect, and it is insulated from other equipment chassis and cases. A safety grounding conductor network (green wires) is carried within the same raceways and cables as the ac power conductors. This network connects these equipments to the equipotential plane, in parallel with ground straps, cable trays, conduits, pipes, building structure, and other metallic support members.

An internal equipotential plane approach is also employed in new construction for signal reference. Again, the HEMP shield serves as this equipotential plane. In multistory buildings, copper grid equipotential planes bonded to the shield may be needed for the upper floors.

Another major requirement on the ground system of a hardened facility is to prevent HEMP-induced transients from entering the protected volume on the ground conductors. This requirement is met by electrically bonding internal ground wires to the inside surface of the shield and bonding external grounds to the outside surface of the shield. No barrier POEs are required for making these connections. When the ground system-barrier interfaces are implemented in this manner, the interior and exterior parts of the ground system will not affect the HEMP protection. The grounding topology used for HEMP protection is compatible with TEMPEST requirements, since the same process that prevents HEMP transients from entering through the barrier on ground conductors also prevents intelligence-carrying signals from exiting through the barrier on these conductors.

13.3.2 Bonding. Low-impedance bonding paths inside and outside the HEMP barrier must maintain their properties over an extended period of time in order to prevent progressive degradation. Bonding is concerned with those techniques and procedures necessary to achieve a mechanically strong, low-impedance electrical interconnection between metal objects and to prevent the path thus established from subsequent deterioration through corrosion or mechanical weakening.

Two types of bonding are used: direct bonding and indirect bonding. Direct bonding is the establishment of the desired electrical path between the interconnected members without the use of an auxiliary conductor. Electrical continuity is obtained by estab-

lishing a fused metal bridge across the junction (by welding or brazing, for example). Indirect bonding is necessary when physical separation is needed between the elements to be bonded, such as interior equipment and the equipotential ground plane (HEMP shield); bonding straps or jumpers are used.

In a hardened facility, shielded door frames and WBC array frames are directly bonded to the HEMP shield by welding or brazing. All structural metal that comes in contact with the HEMP shield must be directly bonded (welded or brazed) to the shield. Inside the HEMP barrier, any cable trays, pipes, or metallic vents that are in contact with the shield must be directly bonded to the shield at intervals of 15.2 m (50 ft) or less.

The quality of the electrical connection between the POE treatments and the shield is important to their effectiveness in controlling HEMP-induced stresses. While the concept of bonding a conductor to a shield is simple, there are a variety of problems that can arise in practice. MIL-B-5087 (reference 13–7) explains procedures and requirements for proper bonds.

13.3.2.1 Bonding of power filters to the HEMP shield. Consider a typical HEMP power filter such as that shown in figure 132. If the return side of the filter (the filter housing) is not adequately bonded to the HEMP shield, the bond impedance Z_B may be high enough to impair the filter's performance, especially at the higher HEMP frequencies. The filter illustrated is a low-pass filter intended to remove transient HEMP interference

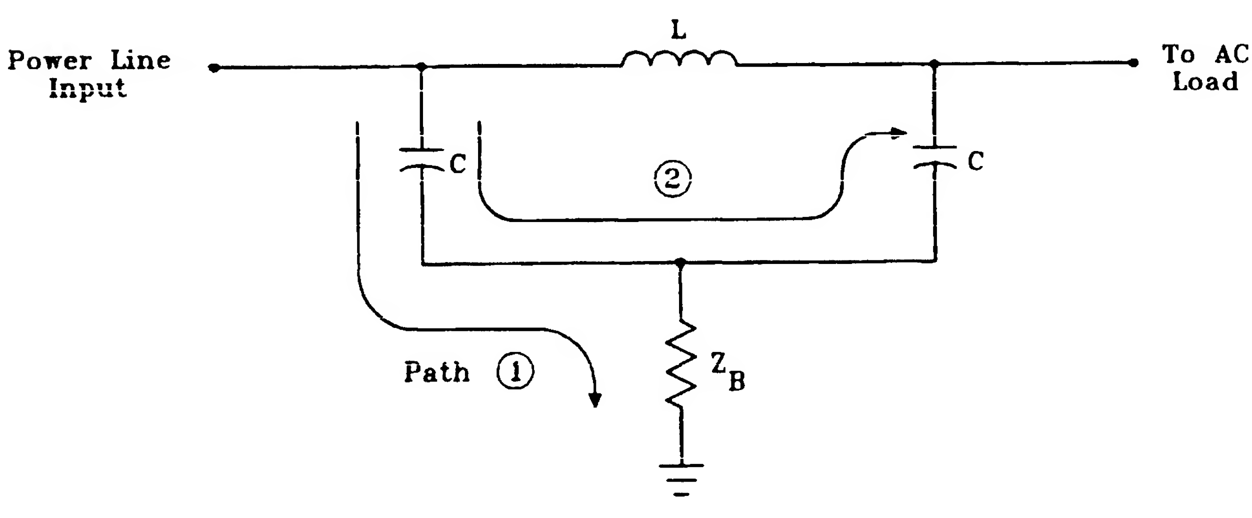

FIGURE 132. Current paths for a low-pass filter.

components from the power line, as is described in section 12. As noted in section 12, every conductor penetrating the HEMP shield (including neutrals and signal returns) must be properly treated with a filter/ESA combination.

In part, the filter achieves its goal by the fact that the capacitive reactance X_c is small at the HEMP frequencies. HEMP transients present on the ac line are shunted to ground along path 1 and, thus, do not reach the load. If Z_B is large relative to X_c, however, HEMP transients will follow path 2 to the load and the effectiveness of the filter is severely compromised. The use of embedded filters, as described in section 12, is intended to minimize problems with power filter bonds.

13.3.2.2 Bonding of conductors to the HEMP shield. As described in sections 9 through 12, the protective devices required at barrier POEs must be peripherally bonded to the HEMP shield. These devices include the frames of shielded doors and equipment access covers for architectural POEs; piping and ventilation WBCs for mechanical POEs; metal column and beam structural POEs; and filter/ESA assemblies, conduits, coaxial cable shields, and communications waveguides for electrical POEs. The requirement to electrically bond ground conductors to the HEMP shield is identified in this section.

In order of desirability, the methods available for bonding these protective devices and conductors to the shield are as follows:

a. Welding and brazing

b. Soldering

c. Clamping (including bolting and riveting), usually requiring an rf gasket

d. Conductive adhesives

Permanent bonds formed by welding, brazing, or soldering are preferred over clamped bonds that depend upon a pressure contact between the metal objects. The reason for this preference is that the permanent bonds will experience much less deterioration over time and will require less maintenance.

The design of all bonds must consider corrosion, including the effects of joining dissimilar metals (see section 15). All bonds to the HEMP shield must be accessible for maintenance.

With few exceptions, MIL-STD-188-125 requires that all POE protective devices be peripherally bonded to the HEMP shield by welding or brazing. The exceptions are made

when the device will become nonfunctional or be damaged by the heat of welding. Soldered bonds are explicitly permitted for joining honeycomb material to the frame of a WBC array panel. Clamped joints are allowed between a shielded door and its frame and for equipment access covers, when the expected frequency of use is greater than once per three years. Coaxial cable shields and communications waveguides may be soldered or clamped to the HEMP shield, when welding or brazing is not possible.

Ground conductors should be bonded to the HEMP shield by welding or brazing, including the exothermic process. Figure 133 shows typical bond configurations that can be implemented with an exothermic weld.

13.3.2.3 Impedance of bonding straps. As emphasized in section 12, it is very important to minimize the length of interconnections that must carry HEMP transients. MIL-HDBK-419 presents the issue of bonding impedance in great detail. An example from that handbook shows that the inductive reactance of a common hookup wire only 15 cm (6 in) long is about 100 Ω at 100 MHz. This is clearly much higher than the resistance of the wire, and will greatly affect the performance of surge arresters and other devices that must be indirectly bonded.

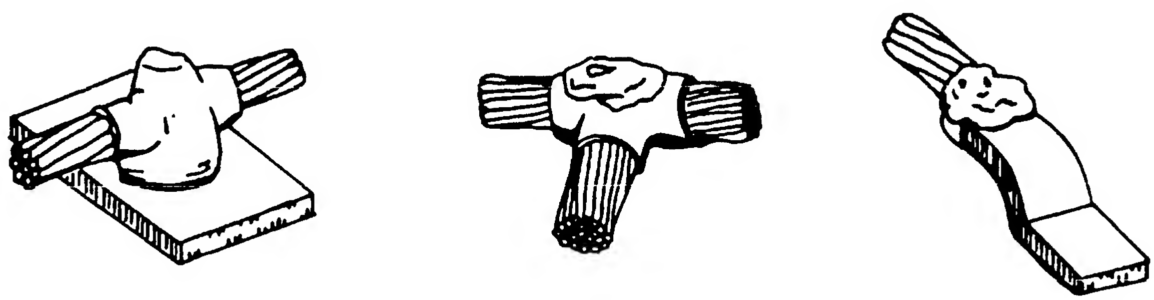

FIGURE 133. Typical exothermic bond configurations (reference 13-2).

13.4 References.

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13-2. "Military Handbook - Grounding, Bonding, and Shielding for Electronic Equipments and Facilities," MIL-HDBK-419 (effective), Dept. of Defense, Washington, DC.

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14. SPECIAL PROTECTIVE MEASURES

14.1 Basic principles.

14.1.1 Introduction. MIL-STD-188-125 (reference 14-1) states that "... protection against the HEMP threat environment specified in DoD-STD-2169 shall be achieved with an electromagnetic barrier and with additional special protective measures as required." The barrier consists of the HEMP shield and protective devices or treatments to prevent or limit HEMP energy from entering the protected volume at the shield points-of-entry. Two or more barriers and protected volumes may be used when equipments to be hardened are physically separated. All other hardening measures are encompassed within the generic term "special protection."

Special protective measures are to be used only as a last resort. They cannot substitute for an electromagnetic barrier which meets the MIL-STD-188-125 requirements. Furthermore, mission-essential equipment that can satisfactorily operate in the protected volume cannot be placed outside the barrier and protected with special measures.

This section addresses the design of special protective measures. They are denoted as "special" because they must be specially tailored to suit each particular hardening application. Since it is impractical to cover every situation that might be encountered, general approaches and examples will be presented.

14.1.2 Requirements for special protection. An ideal HEMP-hardened facility consists of mission-essential equipment entirely housed within a perfect electromagnetic barrier. Even if a high-altitude nuclear detonation occurs, the electromagnetic environment in the protected volume will remain undisturbed, and operation of the sheltered equipment will be unaffected. No special protective measures are needed.

Low-risk hardening approaches the ideal configuration, but accounts for operational exceptions (MEE that cannot function inside a shield) and engineering constraints (unattainable isolation performance) with special protective measures. Real defense facilities depart from the ideal case in three ways that dictate special protective requirements. These types of differences are enumerated in MIL-STD-188-125, are schematically illustrated by figure 134, and are explained in somewhat greater detail by handbook subsections 14.1.2.1 through 14.1.2.3.

14.1.2.1 Mission-essential equipment outside the electromagnetic barrier. The first and most obvious difference from the ideally hardened facility configuration is that some

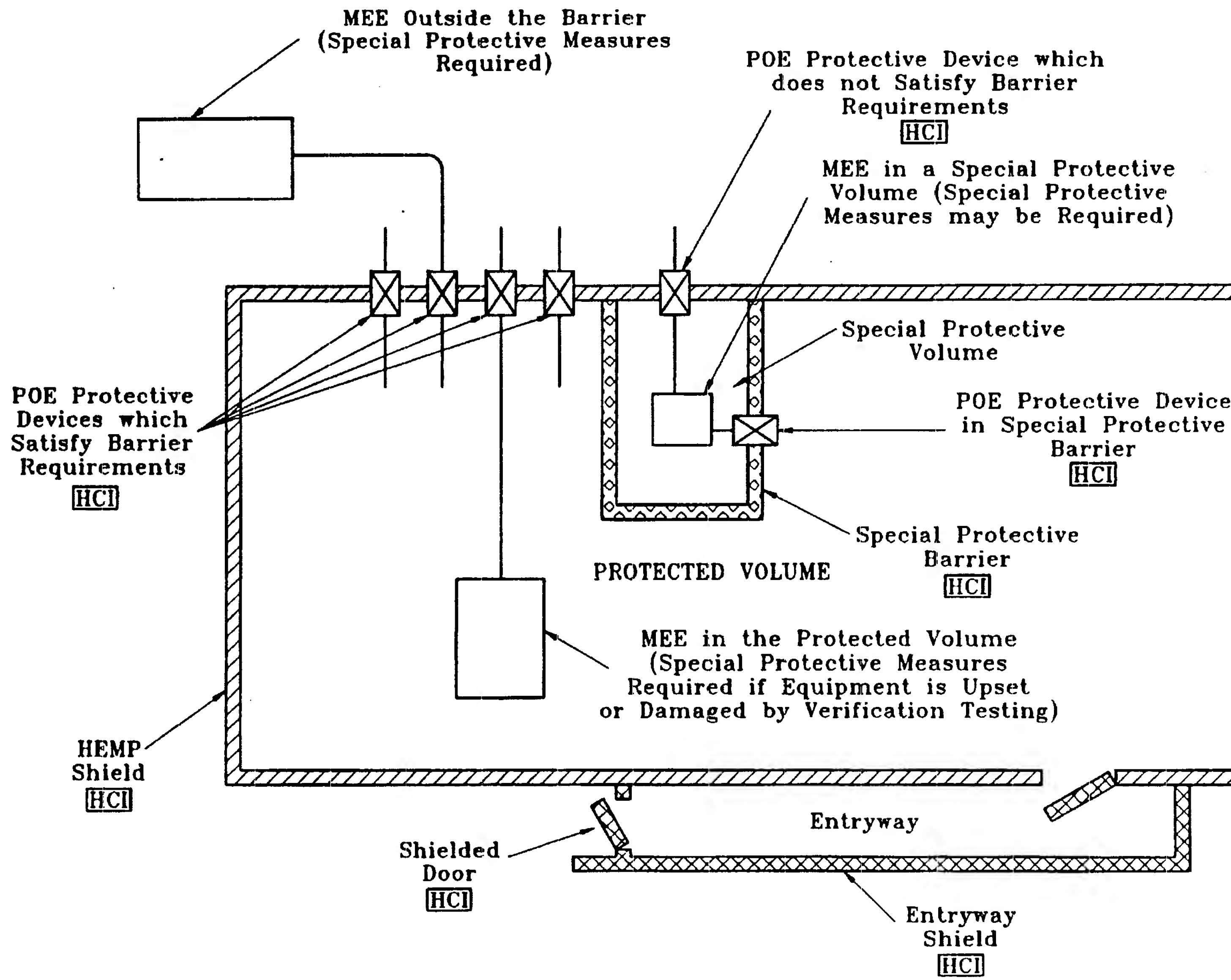


FIGURE 134. Illustration of special protective requirements.

mission-essential equipment must be placed outside the electromagnetic barrier. Radio wave transmission, for example, requires an unobstructed rf propagation path between the sending and receiving antennas; the communications linkage simply cannot be completed if either antenna is inside a metallic shielded enclosure.

Externally placed MEE receives no HEMP protection from the electromagnetic barrier, even if the shield and penetration treatments are perfect. Special protective measures must therefore be implemented to enable such equipment to survive in the full DoD-STD-2169 (reference 14–2) environment to which it may be exposed.

The MIL-STD-188-125 low-risk approach recognizes functional necessity as the only valid reason for locating MEE external to the electromagnetic barrier.[4] The antenna example, presuming the associated communications traffic to be mission-essential, satisfies this criterion. Other such exceptions may include the following items:

a. Heat exchangers generating waste heat or water vapor in excess of amounts which can practically be handled by the building heating, ventilating, and air conditioning subsystem

b. A deep well pump providing makeup water

c. External security sensors

Only the component or components that are functionally required to be outside can be treated with SPMs. Thus, while the antenna can be external to the barrier, antenna-mounted electronics and positioning circuit elements must be enclosed. Similarly, although the heat exchanger fan motor and the well pump motor are outside, wiring and control circuits should be within a protected volume.

Note that restrictions on placing equipment outside the barrier apply and special protective measures are needed only when the equipment is designated as mission-essential.

14.1.2.2 Sensitive mission-essential equipment inside the electromagnetic barrier. Barrier shielding effectiveness and transient suppression/attenuation performance specified by MIL-STD-188-125 results from tradeoffs between cost, engineering feasibility, and risks of electromagnetic upset or damage to generic electrical and electronic equipment. Although the isolation requirements are stringent, the barrier is not perfect. This represents

[4]This is a fundamental principle of the low-risk approach. Installations other than C[4]I facilities performing time-urgent missions may consider additional factors, such as inherent equipment resistance to electrical overstress. However, these higher-risk hardening techniques are not appropriate for facilities covered by MIL-STD-188-125.

the second departure from ideal hardening, and it implies that the "benign" environment in the protected volume will contain nonzero residual internal electromagnetic stresses from a HEMP exposure.

Since the standard establishes no minimum vulnerability threshold for internal equipment, satisfactory barrier performance does not guarantee undisturbed operation of MEE in the protected volume. Unusually sensitive equipment—hardware unable to tolerate the small residual transients—does exist, but is rare. SPMs must then be provided to protect such equipment.

Unusually sensitive equipment can be identified either in the design phase or during hardness verification testing. In the design stage, verification test reports for previously built facilities containing the same equipment should be reviewed to determine if problems were experienced. Systems intended to operate under extremely quiet electromagnetic conditions should also be assessed for potential vulnerability. If the need can be identified with these methods, the special protection can be provided in the routine course of building design and construction.

Mission-critical systems which experience upset or damage due to verification test excitations will obviously require supplemental hardening. In these instances, the SPMs must be installed under a retrofit program.

14.1.2.3 Special protective volumes and barriers. The third case requiring special protective measures occurs when a POE protective device cannot be designed to satisfy the barrier shielding effectiveness or transient suppression/attenuation specifications without interfering with facility operational performance. The offending device may be a pipe penetration larger than 10 cm (4 in) inside diameter or an electrical POE treatment which produces residual electromagnetic stresses in excess of the PCI test limits.

In such cases, a special protective volume enclosed by a special protective barrier must be established. The special protective barrier restricts the excess field or transient leakage, preventing contamination of the benign electromagnetic environment in the protected volume. Figure 134 illustrates a special protective barrier as a separate shield with protected penetrations. In practice, however, this barrier may be implemented using the metal walls of a closed piping system and cable or equipment cabinet shields.

Special protection of this type is undesirable and should be avoided, if possible, because it is costly and may be a significant operations and maintenance nuisance. It is usually possible to eliminate oversized piping penetrations by one of the following methods:

a. Use two or more pipes in parallel; each of these pipes must satisfy the dimensional requirements.

b. Install a waveguide-below-cutoff array in the oversized pipe, as described in MIL-STD-188-125 and in section 9 of this handbook.

These alternatives should be thoroughly evaluated before accepting the need for a special protective volume.

Options for avoiding a special protective barrier are not always available in the case of electrical POE protective devices. Consider, for example, a 1-kW high-frequency transceiver with operating frequencies from 2 MHz to 30 MHz. When transmitting with a reasonable voltage standing wave ratio into a 50 Ω transmission line, peak voltage on the rf output cable will be of the order of 450 V. These operational circuit parameters place constraints on performance of surge arresters and filters, such that transient suppression/attenuation requirements of MIL-STD-188-125 for rf transmit antenna lines cannot be met with known devices. When no other acceptable alternative exists, a special protective volume and special protective barrier must be provided.

Because electromagnetic stresses in a special protective volume may be significantly larger than those in the protected volume, additional measures are sometimes needed to protect MEE housed within the special protective volume. Methods for determining whether supplementary hardening is required are discussed later in this section.

14.1.3 Specification approaches for special protective measures. Identification and protection of special cases are likely to be the HEMP designer's most difficult hardening problems. Installation configurations and details will vary from site to site, and complete solutions cannot be defined until the exact hardware to be protected is known. This creates unique situations with respect to preparation of the facility drawings and specifications.

There are three basic approaches for stating special protective requirements in the construction project documentation. Each approach has advantages and disadvantages, and none is appropriate for all instances.

The preferred approach is to always provide a "low-risk" design, of such high quality that it will be adequate to protect essentially any components which the contractor selects. This is the 100 dB (nominal) barrier which is used to harden virtually all of the MEE in the protected volume. A low-risk design is provided and specified whenever it is functionally compatible with the item to be hardened. The second and third options are used in those few instances where low-risk hardening is not technically feasible.

The second alternative is to specify particular equipment, by manufacturer and model number, and to provide detailed drawings and specifications of the protection needed for the specific hardware. This technique, of course, limits the competition in bidding the affected portion of the job.

The architect-engineer might also provide drawings and specifications which include the hardening measures appropriate for the generic class of equipment; some examples of this type will be presented later. This option requires the construction contractor to implement the prescribed measures, but relieves him of the responsibility to deliver a hard subsystem. If verification testing later indicates that additional HEMP protection is necessary, the procuring or using agency would be responsible for the required modifications.

No single choice is optimum for all special protective requirements. Risks, schedules, and costs, as well as the technical issues, need to be evaluated on a case-by-case basis to make this decision. The designer's guiding principle must be use of low-risk hardening wherever possible.

Performance requirements for the special hardness critical items and test requirements, methods, and pass/fail criteria for special protective measures must be explicitly written into the construction specifications. All testing required by MIL-STD-188-125 must be included. The architect-engineer must perform tradeoffs between the costs of requiring additional tests and the risks of not performing them. Factors such as mission criticality of the equipment, number of units to be procured, past experience with the type of device and probable vendors, and cost/schedule impacts of a possible failure in the future verification program should be considered in this evaluation.

14.1.4 Design approach for special protective measures. As indicated earlier, special protective measures are "special" because the hardening must be tailored for each particular application. Mission-critical electrical and electronic circuits must be protected with a low-risk approach inside an electromagnetic barrier, but some MEE such as antennas and air conditioning condensers will remain outside the shield. Hardening treatments for an antenna are obviously different from those required for an air conditioning condenser, and the protection can also vary for MEE of the same type supplied by different manufacturers. Similarly, there are a variety of techniques for constructing special protective barriers. Special protective measures represent the exceptions to the "one size fits (nearly) all" HEMP barrier concept, which is the cornerstone of low-risk hardening.

Because special protection addresses a virtually infinite variety of one-of-a-kind situations, this handbook is unable to provide specific solutions. Instead, this section presents a generic special protective design approach to be used when the specific equipment and

threat exposure geometry have been identified. The recommended method for hardening MEE (figure 135a) is a straightforward electromagnetic analysis/test and design procedure, consisting of the following elements:

a. Identify the requirement for special protective measures.

b. Ensure that use of SPMs is minimized by subdividing the equipment into two parts: one part consisting of those elements which can be located inside a barrier and the second which must functionally be outside. In this manner, MEE outside the barrier will be limited to a very few components.

c. Predict the reasonable worst case electromagnetic field environment to which the MEE may be exposed in a HEMP event. This is the radiated electromagnetic stress on the equipment.

d. Experimentally measure or calculate the coupling from the field environment to equipment conductors. These are the conducted transient stresses on the equipment.

e. Determine MEE vulnerability thresholds by test or analysis. These vulnerability thresholds are also known as the equipment electromagnetic strength.

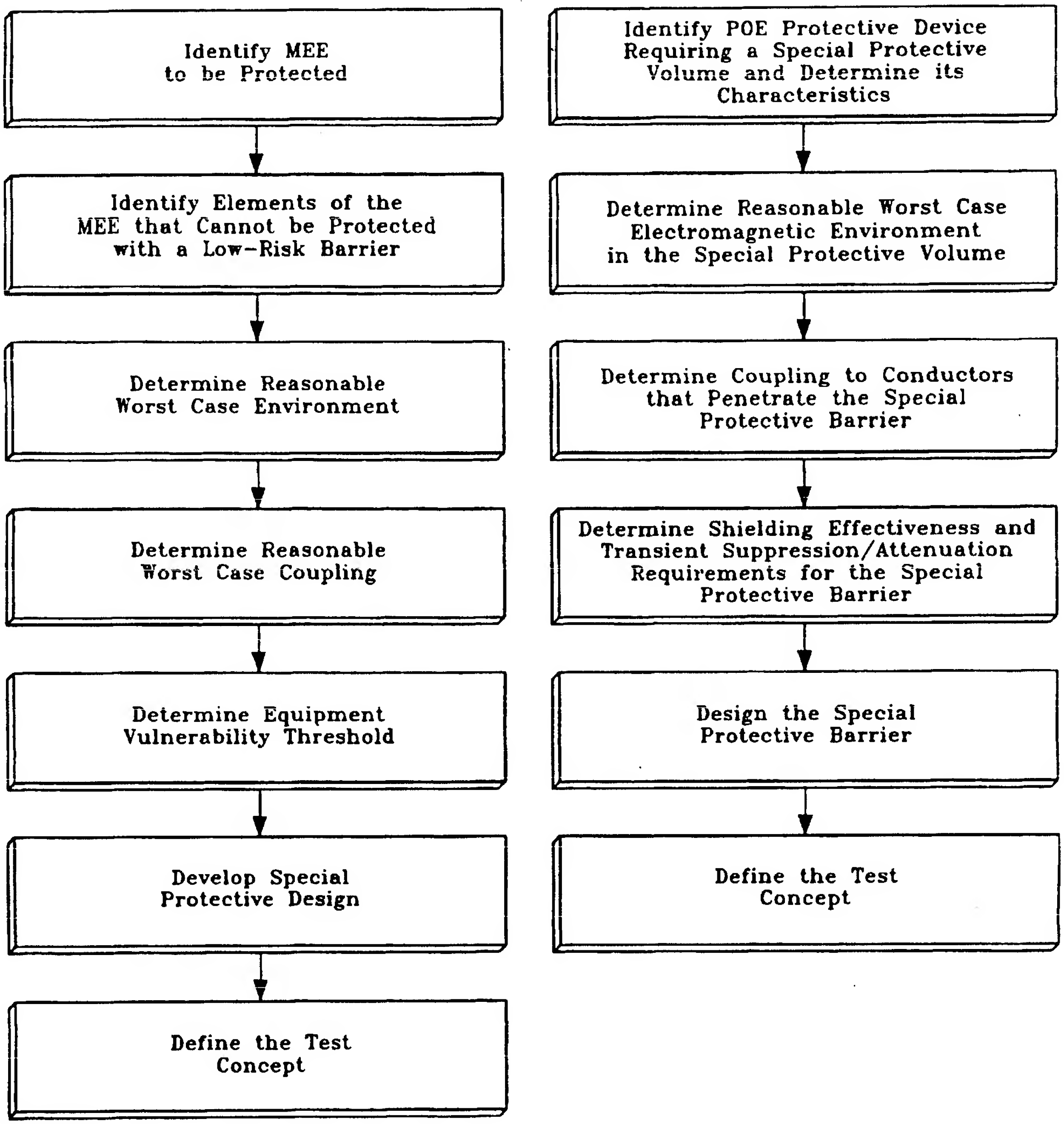
f. Design or select hardness-critical items to reduce the electromagnetic stresses or increase the equipment strength, until an adequate margin of safety is attained. Note that MIL-STD-188-125 requires a 20 dB margin for conducted transient stresses.

g. Define the test concept for demonstrating effectiveness and margin of the hardened design and incorporate the necessary features to ensure testability.

Many volumes of information have been written on each of these topics; selected references will be cited in the subsequent paragraphs. It is not practical, however, to include the entirety of the technical discipline in these pages. Descriptions of the steps in this process assume the equipment to be communications-electronics hardware in the protected volume or in a special protective barrier. MEE outside the shield should include only antennas, motors, sensors, and other discrete components.

Figure 135b illustrates the approach for determining shielding effectiveness and transient suppression/attenuation requirements for a special protective barrier. The design must ensure that residual stresses in the protected volume remain within the allowable limits.

The technical requirements for designing SPMs indicate the need for engineers with expertise in electromagnetic protection to be a part of the design team. Facility architec-



a. Design process for hardening MEE with special protective measures.

b. Design process for special protective barriers.

FIGURE 135. Design approach.

tural, mechanical, and electrical designs require qualified architects and mechanical and electrical engineers, respectively, and special protective designs also need competent specialists. This statement applies to the Government agency responsible for reviewing and approving drawings and specifications, as well as the organization contracted to prepare them.

14.1.4.1 Environments analysis. Figure 136 illustrates the environments analysis problem topologically. A bounding surface between the "equipment" and the "environment" must be defined. It may be a physical surface such as a rack or special protective barrier, or it may be any imaginary surface which encloses the equipment to be hardened. The goal of the environments task is to determine reasonable worst case electromagnetic fields and conducted transients which are incident on the boundary from outside and couple across the boundary to the equipment.

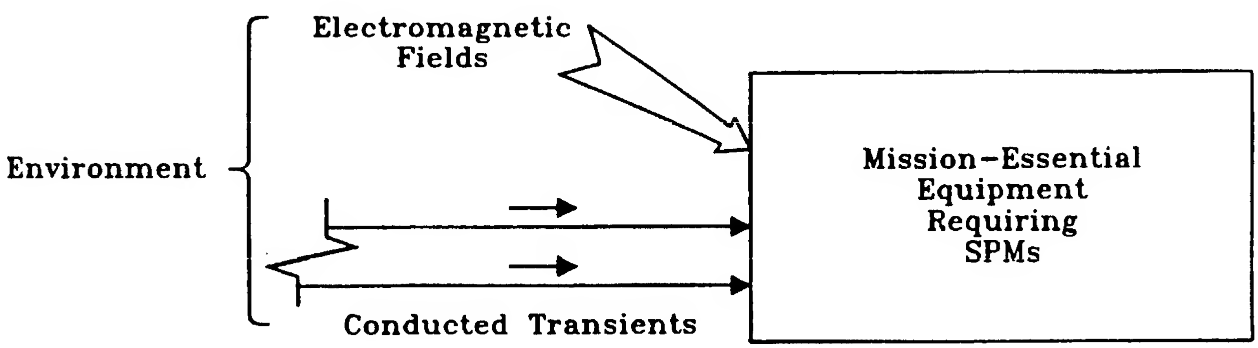


FIGURE 136. **Environments analysis task.**

Generally, for MEE outside the electromagnetic barrier, DoD-STD-2169 threat fields and reasonable worst case long-line transients (those specified in MIL-STD-188-125 as drives for PCI test procedures) are used as the environment. In selected cams, however, reduced stresses due to equipment burial or shadowing and less efficient coupling geometries may be appropriate.

For MEE in the protected volume, both DoD-STD-2169 fields attenuated by the minimum shielding effectiveness requirement and the maximum allowable residual internal transient responses constitute the environment in most circumstances. The exceptions occur when the equipment boundary is inside another layer of electromagnetic isolation.

The environment in a special protective volume will be determined by isolation characteristics of the device or devices which create the requirement for that special protective volume. Measurements or predictions of these fields and conducted transients must, therefore, be performed on a case-by-case basis.

14.1.4.2 Coupling experiments and analysis. A ground-based C^4I facility interacts with an electromagnetic environment in which it is immersed as one large complex "antenna," consisting of the structure, the equipment, and all conducting appendages. This antenna includes power, communications, and other cables and utility piping such as water, sewer, and fuel lines. The applied electric and magnetic fields induce current and charge distributions through the system. Amplitude and frequency content of the response at a given point depend upon the coupling geometry of the entire site, conductivity and other electrical parameters of the soil, and the field structure of the excitation.

To determine the electromagnetic stresses against which special protection must be provided, the designer must perform coupling experiments or analyses. Experiments are strongly encouraged, where practical, because the accuracy of analytical predictions for complex geometries is generally limited due to approximations necessary for modeling.

When an experimental approach is chosen, both low-level methods and high-level, threat-like simulators can be considered. The cw immersion technique, which is described in section 16, is a lower level method providing threat-relatable measurements, and it is often very cost effective. The low-level responses can be extrapolated to threat-level using analytical methods. High-level HEMP simulators provide improved threat fidelity, although some data processing to account for simulation deficiencies and less than reasonable worst case conditions is still required. High-level testing is particularly useful for equipment with nonlinear response characteristics. These simulators are operated by the Defense Nuclear Agency and the service centers of HEMP expertise, which are identified in section 21, "HEMP Program Management."

The analytical approach involves solving electrodynamics equations for the applicable environment and the specific coupling geometry. Many mathematical treatments have been developed for this purpose; the U.S. Air Force Weapons Laboratory Interaction Note series (reference 14–3) contains several hundred technical papers on this subject. IEEE Transactions on Nuclear Science, on Antennas and Propagation, and on Electromagnetic Compatibility are also excellent sources.

In general, development of a complete site model has not been found to be a useful approach to coupling analysis. Practical computing constraints require too many compromises in representing such a complex geometry. A more practical technique is to model

only that part of the facility and the equipment of particular interest, including coupled stresses from the rest of the facility as conducted transient sources. The principal features are then represented by antennas and transmission lines, with coupling configurations and parameters chosen to give reasonable worst case responses. Reference 14–4 is a particularly useful source for this type of modeling. Properly formulated, this analysis will produce an upper bound for transients induced on the equipment conductors.

When practical, hardening against upper bound stresses should be provided. If this results in an excessively expensive or technically infeasible design, the coupling experiment or model should be refined to give more accurate (rather than bounding) results.

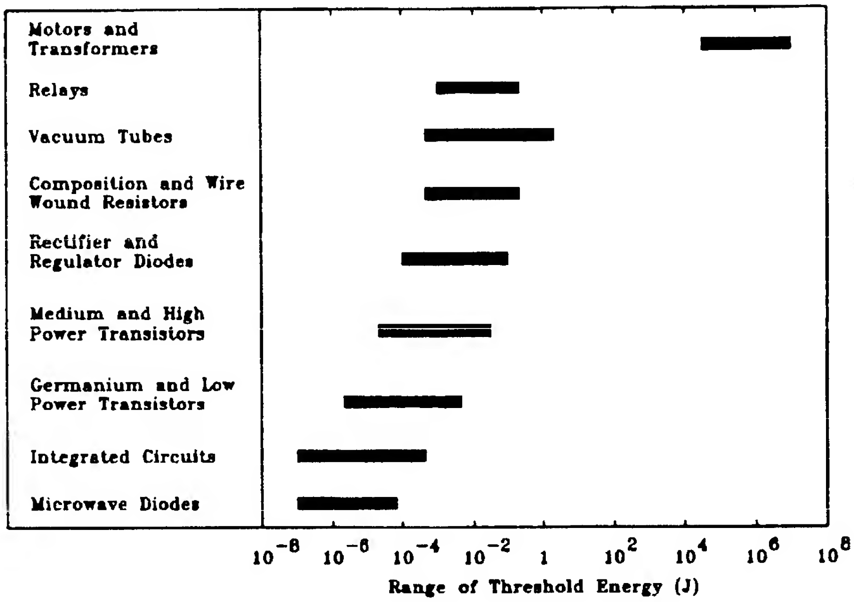
14.1.4.3 Equipment vulnerability experiments and analysis. Vulnerability of electrical and electronic subsystems to a HEMP exposure refers to the damage or upset of circuit components. Damage is a permanent condition rendering the equipment inoperable or degraded below useful limits until repair or replacement is effected. An upset is the introduction of spurious transients that disrupt normal operation until an automatic or manual reset occurs. Examples include erroneous bits in a data stream, interference in digital logic sequences, erasure of computer-stored information, and opening of circuit breakers. Unless recovery can be accomplished within operationally required timelines, upsets may be as mission-aborting as damage. Physical damage to mechanical subsystems can sometimes result from arcing or resistive heating.

The minimum electromagnetic stress that can cause such damage or upset to an equipment is known as its vulnerability threshold. This characteristic can be determined by experimental or analytical means. Figure 137 presents typical vulnerability thresholds for some generic components. Note that semiconductor devices are much more sensitive than other types of components. Fortunately, it is almost always possible to shield these more vulnerable elements.

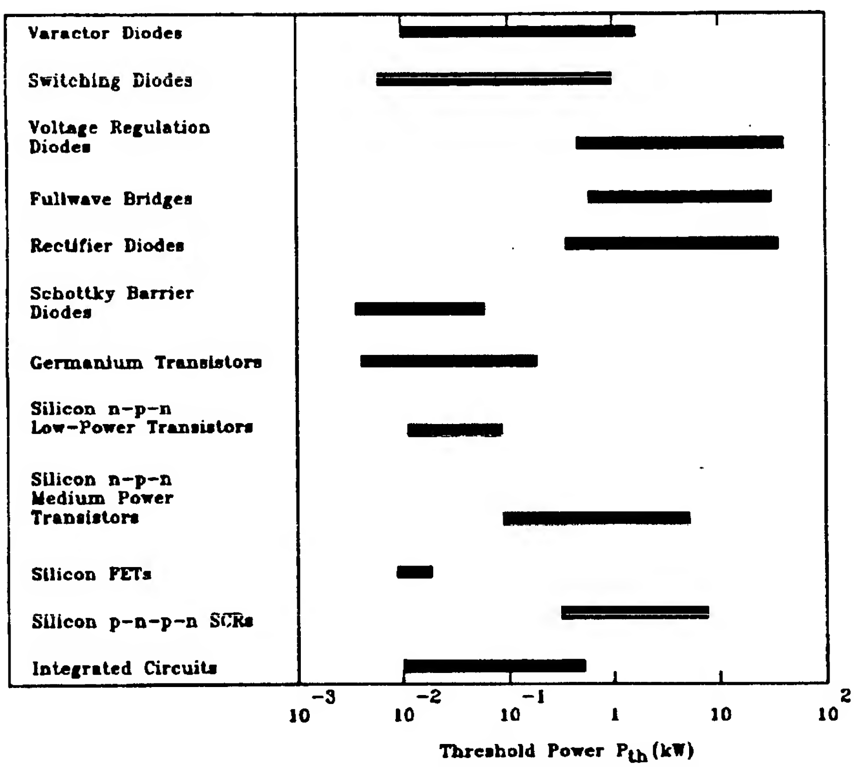
For HEMP barriers constructed to MIL-STD-188-125 requirements, threshold determinations are needed only for equipment hardened with special protective measures. There are many methods for estimating threshold values, including the following:

a. Experience indicates that equipment will not be damaged or upset by voltage and current transients that are a small fraction (10-50 percent) of the normal operating levels, even though the spectral characteristics of the transient may be significantly different from those of the operating signal.

b. Test signal strength, for equipment which has been subjected to electromagnetic susceptibility testing, may be used to estimate thresholds.



a. Comparative energy vulnerability thresholds of common components.



b. Power damage threshold ranges (for a 1-μs pulse) for various semiconductor devices.

FIGURE 137. Typical damage thresholds (reference 14-5).

c. Thresholds may be estimated from data on system-generated transients that the equipment is known to withstand.

d. Experimental or analytical vulnerability assessment.

In an experimental assessment, each interface is injected with transients that are similar in waveform to predictions of the coupled stresses. The maximum signal amplitude that causes no equipment malfunction is then used as the threshold value. Results determined from such experiments are significantly more accurate than vulnerability thresholds calculated by analytical techniques.

The most common form of analytical vulnerability assessment is to determine if the equipment can withstand specified conducted transients—normally ten times the predicted coupled signal level—at each of its external interfaces. The approach is to consider each interface separately and to assess the circuit along each path from the interface to a depth of two or three semiconductor devices. As a first-order screen, it is assumed that the entire interface transient energy is deposited into each component. Component damage thresholds are estimated using the Wunsch-Bell power model (reference 14-6) or other methods. Parts which pass this initial screen are eliminated from further consideration, and more detailed circuit analyses are performed for those which fail. Analytical calculations for simple circuits and network analysis computer codes for more complex arrangements account for attenuation and shunting of transients en route to the potentially vulnerable device.

Such predictions relying on generic data base characteristics can be inaccurate. These inaccuracies can be reduced by the measurement of component/piece-part characteristics. An alternative is to use analytical methods to determine the power threshold at which a piece of equipment will fail. This is inherently more difficult than determining if equipment meets a strength specification. Not only do part failures need to be considered, but operational conditions and synergism between parts must be accounted for. A method that addresses equipment failure threshold prediction is presented in reference 14–7.

14.1.4.4 Special protective design development. After a thorough review of the problem confirms that a low-risk topological shielding approach is not possible and SPMs are the only available hardening method, a detailed design must be developed. Based on results of the coupling and vulnerability assessments, the designer must define a hardened configuration capable of withstanding ten times the expected conducted transient stress. The output of this task consists of answers to the following questions:

a. What hardness critical items and hardness critical processes or procedures are needed?

b. Where should hardness critical items be installed?

c. What are the performance requirements needed to provide the specified margin?

MIL-STD-188-125 allows a broad latitude in selection of special protective measures, so long as reliability, maintainability, safety and human engineering, and testability requirements are satisfied. A special protective barrier may be implemented as a separate shield with protected penetrations or using the inherent electromagnetic isolation features of the piping, cable, and equipment installations. A wide spectrum of stress reduction and strength enhancement methods are explicitly listed in the protection standard. Even recycling by automatic or manual actions is permitted, when these can be accomplished within the time-urgent mission profile.

The key step in the design process is a well-documented analysis, in accordance with the requirements of data item description DI-ENVR-80266, DI-ENVR-80267, or DI-NUOR-80927. This report provides a complete audit trail from the survivability criteria to the hardened design, allowing independent evaluation of conclusions by the reviewer. It also serves as the basis for developing quality assurance, acceptance, and verification test requirements.

14.1.5 Testing concepts for special protective measures. The reasons for HEMP testing specified by MIL-STD-188-125 for special protective measures are the same as the reasons specified for primary barrier testing. They are:

a. To demonstrate that hardness critical items provide the specified performance (quality assurance and acceptance testing)

b. To verify that HCI performance is adequate to provide mission HEMP survivability (verification testing)

Just as the special protective design must be tailored to the specific hardening application, testing must be tailored to the particular hardening design.

The agency or contractor installing special protective measures is required to conduct quality assurance tests to measure HCI performance and ensure that it complies with the design specifications. Acceptance tests for special protective barriers are incorporated into the shielding effectiveness and PCI acceptance test procedures. These tests are described in section 16.

Verification testing of special protective measures involves much more than a simple demonstration of HCI performance in-situ. It includes coupling measurements to verify

the validity of assumptions and approximations and to confirm the accuracy of the coupling estimates. Measured responses, threat-extrapolated as necessary, are then used to specify pulse current injection levels on conductors of the MEE. Injection tests at 10 times the predicted stresses (or worst case PCI values, whichever are smaller) verify the assumptions, approximations, and accuracy of the equipment vulnerability determination. Further discussion of the verification test sequence is found in section 16.

14.2 MIL-STD-188-125 requirements.

5.1.8 Special protective measures. In special cases where HEMP hardness cannot be achieved with the electromagnetic barrier alone (see 4.3.4), special protective measures shall be implemented. Special protective measures shall not be used as a substitute for an electromagnetic barrier which satisfies the performance requirements of this standard.

5.1.8.1 Mission-essential equipment outside the electromagnetic barrier. Special protective measures shall be implemented to HEMP harden mission-essential equipment which is placed outside the electromagnetic barrier in accordance with provisions of this standard (see 5.1.1.1). Special protective measures for MEE outside the barrier may include:

a. Cable, conduit, and local volume shielding

b. Linear and nonlinear transient suppression/attenuation devices

c. Equipment-level hardening (reduced coupling cross-section, dielectric means of signal and power transport, use of inherently robust components)

d. Remoting sensitive circuits to locations within the protected volume

e. Automatic recycling features or operator intervention schemes, when the mission timeline permits

f. Other hardening measures appropriate for the particular equipment to be protected

Performance requirements for the special protective measures shall ensure that HEMP-induced peak time-domain current stresses at the equipment level are at least 20 dB less than the vulnerability thresholds of the equipments.[5]

[5]See MIL-HDBK-423 for methods to determine vulnerability thresholds and guidance in applying the 20 dB margin.

5.1.8.2 Mission-essential equipment inside the electromagnetic barrier. Special protective measures shall be implemented to HEMP harden mission-essential equipment which is within the electromagnetic barrier, but experiences mission-aborting damage or upset during verification testing. Special protective measures for MEE inside the barrier may include cable, conduit, and volume shielding, transient suppression/attenuation devices, equipment-level hardening, automatic recycling, operator intervention features, and other hardening measures appropriate for the particular equipment to be protected. Performance requirements for the special protective measures shall ensure that HEMP-induced peak time-domain current stresses at the equipment level are at least 20 dB less than the vulnerability thresholds of the equipment.

5.1.8.3 Special protective volumes.

5.1.8.3.1 Special protective volumes for piping POEs. When a piping POE waveguide-below-cutoff must be larger than 10 cm (4 in) to provide adequate fluid flow and a waveguide-below-cutoff array insert cannot be used, a special protective volume shall be established inside the electromagnetic barrier (figure 6).

5.1.8.3.1.1 Special waveguide requirements. A waveguide-below-cutoff which must be larger than 10 cm shall be of the minimum inside diameter consistent with its functional requirements. The length of the waveguide section shall be at least jive times the inside diameter. All joints and couplings in the waveguide section shall be circumferentially welded or brazed and the waveguide shall be circumferentially welded or brazed to the facility HEMP shield at the POE. No dielectric lining shall be permitted in the waveguide section.

5.1.8.3.1.2 Special protective barrier for piping FOES. A special protective barrier shall completely enclose piping which is protected at its POE with a waveguide-below-cutoff larger than 10 cm in inside diameter. The special protective barrier may be a separate shield with protected penetrations or it may be implemented using the metal walls of the piping system itself. Performance requirements for the special protective barrier shall ensure that the total shielding effectiveness, measured through the primary electromagnetic barrier and special protective barrier, satisfies at least the minimum requirements shown in figure 1.

5.1.8.3.2 Special protective volumes for electrical FOES. When an electrical POE protective device cannot be designed to achieve the transient suppression/attenuation performance prescribed for the class of electrical POE (see 5.1.7) without interfering with operational signals it is required to pass, a special protective volume shall be established inside the electromagnetic barrier (figure 6).

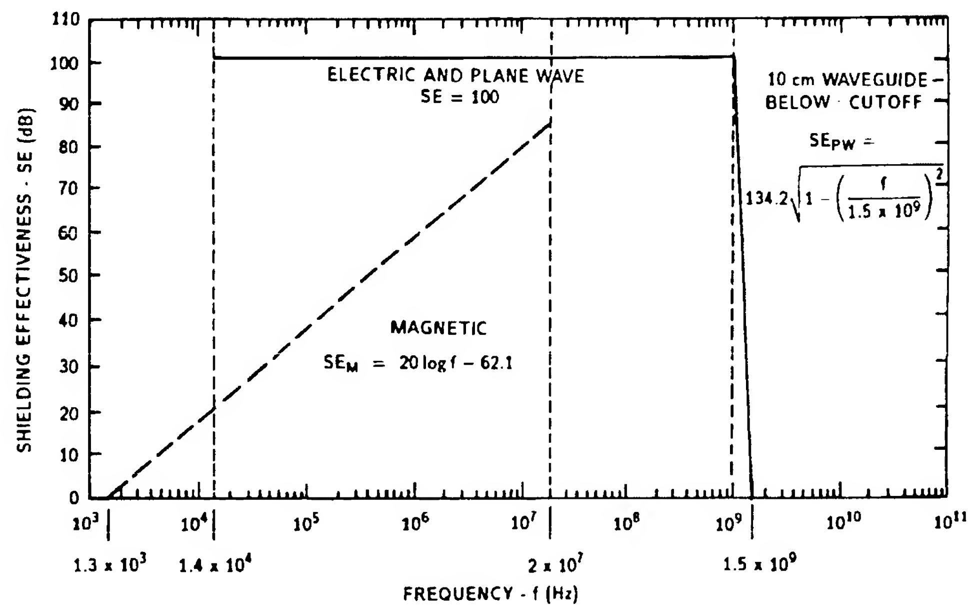


FIGURE 1. Minimum HEMP shielding effectiveness requirement (measured in accordance with procedures of appendix A).

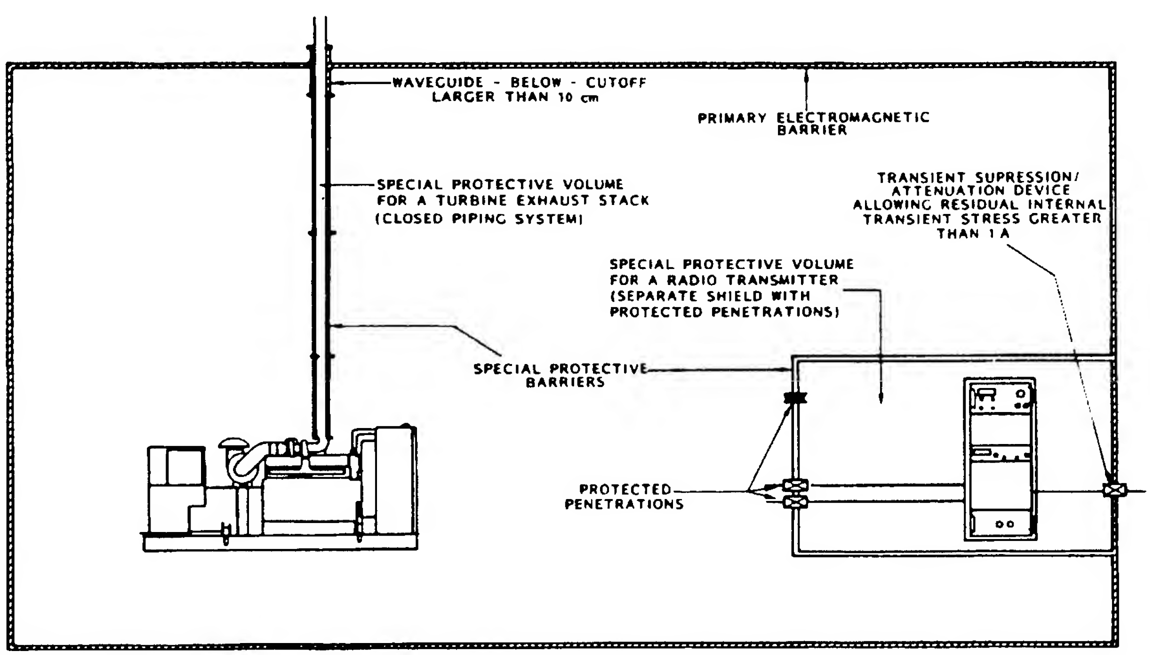


FIGURE 6. Typical special protective volumes.

5.1.8.3.2.1 Special electrical POE protective device requirements. An electrical POE protective device which cannot achieve the prescribed transient suppression/attenuation performance shall be designed to provide the maximum transient suppression/attenuation consistent with its functional requirements. When the pulse prescribed for the class of electrical POE occurs at the external terminal, the POE protective device shall perform in accordance with its design and the device shall not be damaged or degraded.

5.1.8.3.2.2 Special protective barrier for electrical POEs. A special protective barrier shall completely enclose wiring and equipment directly connected to an electrical POE protective device which cannot achieve the transient suppression/attenuation performance required by 5.1.7. The special protective barrier may be a separate shield with protected penetrations or it may be implemented using cable and conduit shields and equipment cabinets. Performance requirements for the special protective barrier shall ensure the following:

a. That the total shielding effectiveness, measured through the primary electromagnetic barrier and special protective barrier, satisfies at least the minimum requirements of figure 1.

b. That the total transient suppression/attenuation, measured through the primary electromagnetic barrier and special protective barrier, satisfies at least the minimum requirements of 5.1.7.

5.1.8.3.2.3 Mission-essential equipment in a special protective volume. Special protective measures shall be implemented as necessary to harden mission-essential equipment in a special protective volume to the HEMP-induced signals which will occur in that volume. Special protective measures for MEE in a special protective volume may include cable, conduit, and volume shielding, transient suppression/attenuation devices, equipment-level hardening, remoting sensitive circuits, automatic recycling, operator intervention features, and other hardening measures appropriate for the particular equipment to be protected. Performance requirements for the special protective measures shall ensure that HEMP-induced peak time-domain current stresses at the equipment level are at least 20 dB less than the vulnerability thresholds for the equipments

5.1.8.4 Quality assurance for special protective measures. Quality assurance tests shall be conducted to ensure that special protective measures comply with performance requirements for the particular installation.

5.1.8.5 Acceptance testing for special protective measures.

5.1.8.5.1 Special protective measures for mission-essential equipment. Acceptance testing is not required for equipment-level special protective measures installed on MEE in accordance with 5.1.8.1, 5.1.8.2, and 5.1.8.8.2.9. HEMP hardness provided by these special protective measures shall be demonstrated during the verification test program.

5.1.8.5.2 Special protective barriers. Acceptance testing for all special protective barriers shall be conducted using shielding effectiveness test procedures of appendix A. Additionally, acceptance testing for all special protective barriers required because of an electrical POE protective device shall include pulsed current injection in accordance with test procedures of appendix B.

The intent of MIL-STD-188-125 requirements regarding special protective measures is to preclude their use except in cases where functional necessity and technology constraints permit no other alternatives. This intent is clearly reflected in restrictions on placing MEE outside the electromagnetic barrier.

The same philosophy is evident in the language related to special protective volumes. If a waveguide-below-cutoff piping penetration must be larger than 10 cm (4 in), it must be of the minimum inside diameter consistent with its function. Similarly, any electrical POE protective device that cannot meet the PCI test requirements must provide the maximum practical transient suppression/attenuation.

Great latitude in selecting hardening techniques for external MEE, unusually vulnerable equipment in the protected volume, or MEE within a special protected volume is allowed. However, because of uncertainties in coupling and vulnerability determinations and the increased difficulty of maintaining special protective measures, a 20 dB margin of equipment conducted transient strength over the reasonable worst case conducted transient stress is required.

14.3 Applications.

14.3.1 General design guidance. Each case requiring special HEMP protective measures must be individually identified and evaluated, and an appropriate hardened design must be developed. In the spirit of the standard, the first step in the process should always be an attempt to avoid the need for special protection by reevaluating the system configuration. MEE outside the barrier or in a special protective volume should be relocated into the protective volume, if possible. If the entire assembly cannot be relocated, it may be possible to move some of the subassemblies. When equipment cannot be moved inside the

primary electromagnetic barrier, a second electromagnetic barrier and protected volume that encloses all parts of the MEE that will operate inside a shield is created. Similarly, the designer should try again to improve the isolation provided by any POE protective device which does not satisfy the primary barrier requirements. When elimination of the special case is not possible, the approach described in 14.1.4 is implemented.

Every design decision should be evaluated for testability, and a test concept for demonstrating performance and effectiveness should be established. All technical quality versus cost tradeoffs should consider both the hardware and testing elements, and any solution which cannot reasonably be verified must be rejected.

14.3.2 Testing requirements. MIL-STD-188-125 requires the same three categories of testing for special protective measures as prescribed for barrier elements of the HEMP protection subsystem. They are:

a. Quality assurance tests during construction – to ensure that proper materials and components are procured and that they are correctly installed

b. Acceptance tests after construction – to demonstrate that as-installed protective devices satisfy their respective performance specifications

c. Verification tests on the completed facility – to verify that the as-built protective subsystem provides mission HEMP survivability

Language of the test requirements articles for SPMs is necessarily general because it relates to undefined hardening methods. Therefore, specific test procedures and pass/fail criteria must be prepared in parallel with the special protective design by the architect-engineer or construction contractor.

Purchased hardness critical items should be subjected to appropriate quality assurance tests at the factory or upon receipt by the construction/installing contractor or agency. Test procedures and pare/fail criteria to be used should explicitly be included in the item procurement documentation.

The quality assurance program should also provide monitoring of hardness critical installation processes for these special protective devices.

Acceptance tests explicitly required by the standard are those for special protective barriers, and they are performed as part of the barrier shielding effectiveness and pulsed current injection acceptance procedures. Acceptance testing of other special protection is

not precluded, however, and additional acceptance tests should be planned and conducted as determined to be prudent in the engineering judgments of the designer and reviewers.

The verification test method involves coupling measurements and pulsed current injection procedures, as described in MIL-STD-188-125. This test must be carefully planned, weighing technical completeness, simulation fidelity, and costs. Guidance in planning special protection verification, as well as the other testing sequences, is provided in handbook section 16.

14.3.3 Hardening mission-essential equipment outside the electromagnetic barrier. Design and implementation of special protective measures for MEE external to the primary electromagnetic barrier is best illustrated with two common examples, which are encountered at many ground-based facilities. The first of these is a mission-essential antenna subsystem, which cannot be placed in the protected volume. The special protective design for this application is schematically illustrated in figure 138.

The attempt to relocate the entire subsystem inside the primary barrier fails, because it would interfere with functional performance of the antenna. The design then evaluates whether it is possible to move tuning and control circuits into the protected volume. For purposes of this example, antenna location and required proximity of the tuner (or other subsystem components) are assumed to prevent this action.

It is determined that all of the external elements of the subsystem, except the antenna itself, are amenable to a topological approach. A second shielded volume bounded by the tuning circuit enclosure, cable conduits, and the primary barrier interface is therefore created. The long conduit runs from the tuner location to the main building are buried to reduce coupling.

The barrier enclosing this second shielded volume must satisfy the 100 dB (nominal) shielding effectiveness specification and the PCI requirements of MIL-STD-188-125, if possible. Thus, the tuner enclosure should be a welded steel (or brazed copper) shield, and the conduits should be rigid steel with welded joints. The POE protective device on the conductor to the antenna element should also limit residual transients to values allowable in the protected volume.

When it is not technically possible to meet all of these requirements—for example, if the antenna feed line POE protective device cannot meet the PCI requirements—this barrier is designated as a special protective barrier. Shield and conduit construction, however, remain as described above.

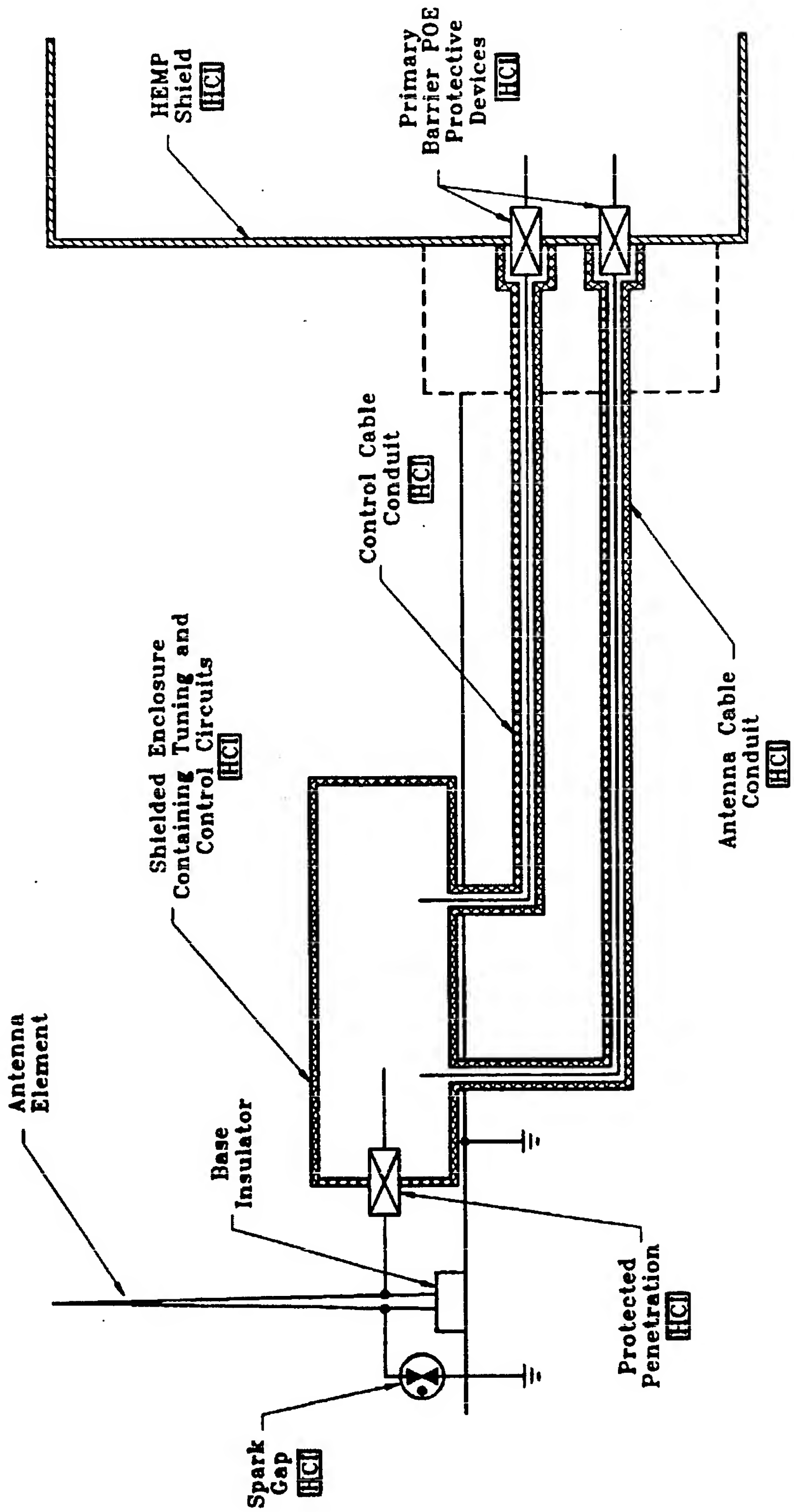


FIGURE 138. Special protective measures for an external antenna subsystem.

The final step in the process is to harden mission-essential equipment which remains outside the topological shield. In the example, this involves the installation of a surge arrester to prevent breakdowns of the base and feedline insulators. The antenna itself is immune to HEMP damage.

The test approach for this installation is straightforward. Quality assurance, acceptance, and hardness verification testing for the tuner enclosure shield, antenna line protective device, and conduits follow the MIL-STD-188-125 procedures for an electromagnetic barrier or special protective barrier, as applicable. Coupling measurements on the antenna are required, and SPM direct drive tests are needed to verify the hardness of the base insulator and feed cable.

The second example is hardening a mission-essential condensing unit (table XI), and the process is virtually identical to that for the antenna subsystem. Selected parts of this subsystem including the water pumps and flowmeters can be located inside the primary electromagnetic barrier. Topological hardening can be applied for protection of external mission-essential wiring and control circuit devices, and a second barrier consisting of shielded enclosures and conduits can be created around these elements. Only a few motors (fan and secondary water pump motors, for example), sensors (sump water temperature and level), or indicators (run lights and pressure gauges) will remain outside. Inherently robust components are selected for these applications, and additional discrete protective devices are installed as necessary.

The condensing unit example illustrates a relatively common occurrence. A barrier enclosing the wiring and control circuits has been established using welded steel shielded enclosures and rigid steel conduits with welded joints. While the fabrication methods are in accordance with the basic requirements for constructing an electromagnetic barrier, the interior dimensions are too small to permit shielding effectiveness measurements as prescribed by MIL-STD-188-125. The barrier must therefore be designated and tested as a special protective measure. The typical verification approach in such a case is PCI testing of the outer surface of this barrier at ten times the measured or extrapolated threat response.

It may further be necessary to place large fuel and cooling water storage tanks outside the primary barrier. The hardening treatment for these cases closely resembles the condensing unit special protective design. Motors, sensors, indicators, and other components are remoted to locations within the protected volume where possible. Mission-essential wiring and control circuit elements remaining outside the barrier are enclosed within a system of rigid steel conduits and shielded boxes. Unshielded components are protected

TABLE XI. Special protective measures for an external condensing unit.

I. Control/Instrumentation Circuits

A. To the extent practical, control and instrumentation circuits should be remoted to stations inside the primary shield.

B. Controls and instruments that cannot be relocated into the protected volume should be housed in shielded enclosures.

C. Fiber optic or pneumatic controls should be substituted for exposed electrical controls, where possible.

D. Remaining exposed electrical controls and sensors should be designed such that failure will result in a "safe"' condition. For example, failure of a sump temperature indicator should turn the pump and fan "'ON.'"

II. Wiring

A. Run all mission-essential wiring that is outside the primary barrier in rigid steel conduit, unless prohibited by vibration or other considerations. Circumferentially weld conduit joints and entries into pull boxes and other shielded enclosures.

B. Use short sections (0.4 m or less) of flexible shielded conduit where necessary for vibration isolation or similar purposes. High-quality conduit with compatible shielded conduit connectors should be used.

C. Noncritical wiring and components outside the system of shielded conduits and enclosures (i.e., heater tapes for water pipes, aircraft warning lights on tall antennas) should be powered from a nonessential feeder that is outside the protected volume, if possible.

III. Enclosures

A. Pull boxes, distribution and control panels, junction boxes, and other electrical enclosures containing mission-essential wiring and circuit components should be shielded enclosures. The enclosures should be constructed of welded steel, with welded or rf-gasketed covers.

B. Exposed gauges. indicator lights. control switches, and other components should be minimized, consistent with safe and proper operation. Components requiring an operator interface are to be installed in a manner that does not violate the shield topology of the conduits and enclosures.

C. Ventilation openings in shielded enclosures should be provided with waveguide-below-cutoff protection.

TABLE XI. Special protective measures for an external condensing unit (continued).

IV. Transient suppression/attenuation devices

A. POE protective devices should be provided on electrical conductors where they leave the shielded topology.

B. Leads on mission-essential motors outside the shield should be protected with fast-acting transient suppressors having an extreme-duty discharge capacity in excess of 4 kA. Similar surge protection should be provided across terminals of mission-essential sensors that are outside the shielded region.

V. Motors and sensors outside the shield

A. Totally enclosed fan-cooled motors in metal casings should be used.

B. Sensors should be mechanical, if practical. Electromechanical sensors may also be used, but electronic sensors employing semiconductor components should be avoided.

with discrete hardening devices. For fuel tanks, transients on conductors entering the tank must be limited to ensure that HEMP-induced arcs cannot ignite the combustible vapors.

14.3.4 Hardening sensitive mission-essential equipment inside the barrier. Mission-aborting upsets of equipment in the protected volume due to PCI injections outside the barrier are expected to be rare, assuming that POE protective devices satisfy the MIL-STD-188-125 requirements. The likelihood of occurrences of damage is thought to be extremely low. This is because residual HEMP stresses entering through an acceptable barrier are not significantly greater than fields radiated by common equipment and natural or system-generated transients.

Partly for the reason given above, and partly because few power-on PCI tests have been conducted to date, actual experience of this type is very limited. In a known case, a commercial computer intended to operate in an electromagnetically quiet environment was identified in the design stage. Protection was installed during facility construction using the shield-within-a-shield concept shown by figure 139, to meet electromagnetic compatibility and electromagnetic pulse survivability criteria. This approach is technically sound and is recommended when unusually sensitive equipment is identified before construction begins.

If a problem is found during verification testing, corrective actions must be taken. The POE protective device should be repaired or replaced if it is determined to be deficient. However, if the barrier element is satisfactory according to the requirements of MIL-STD-

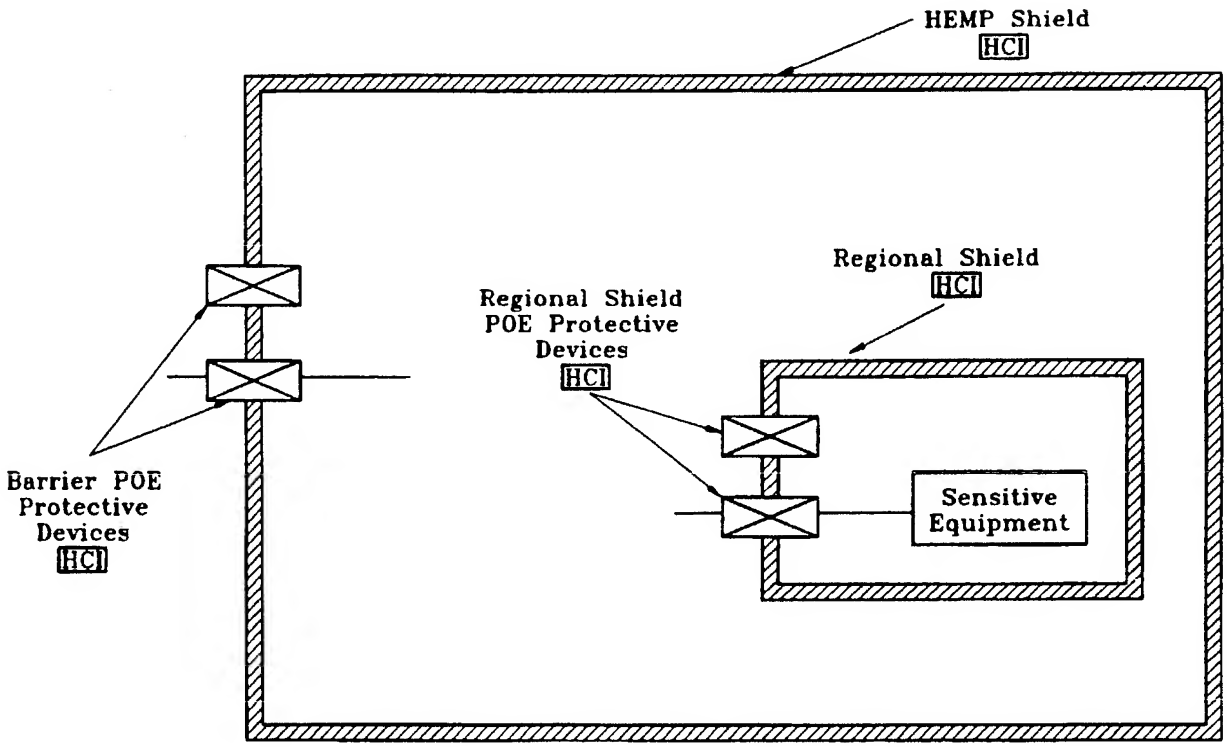


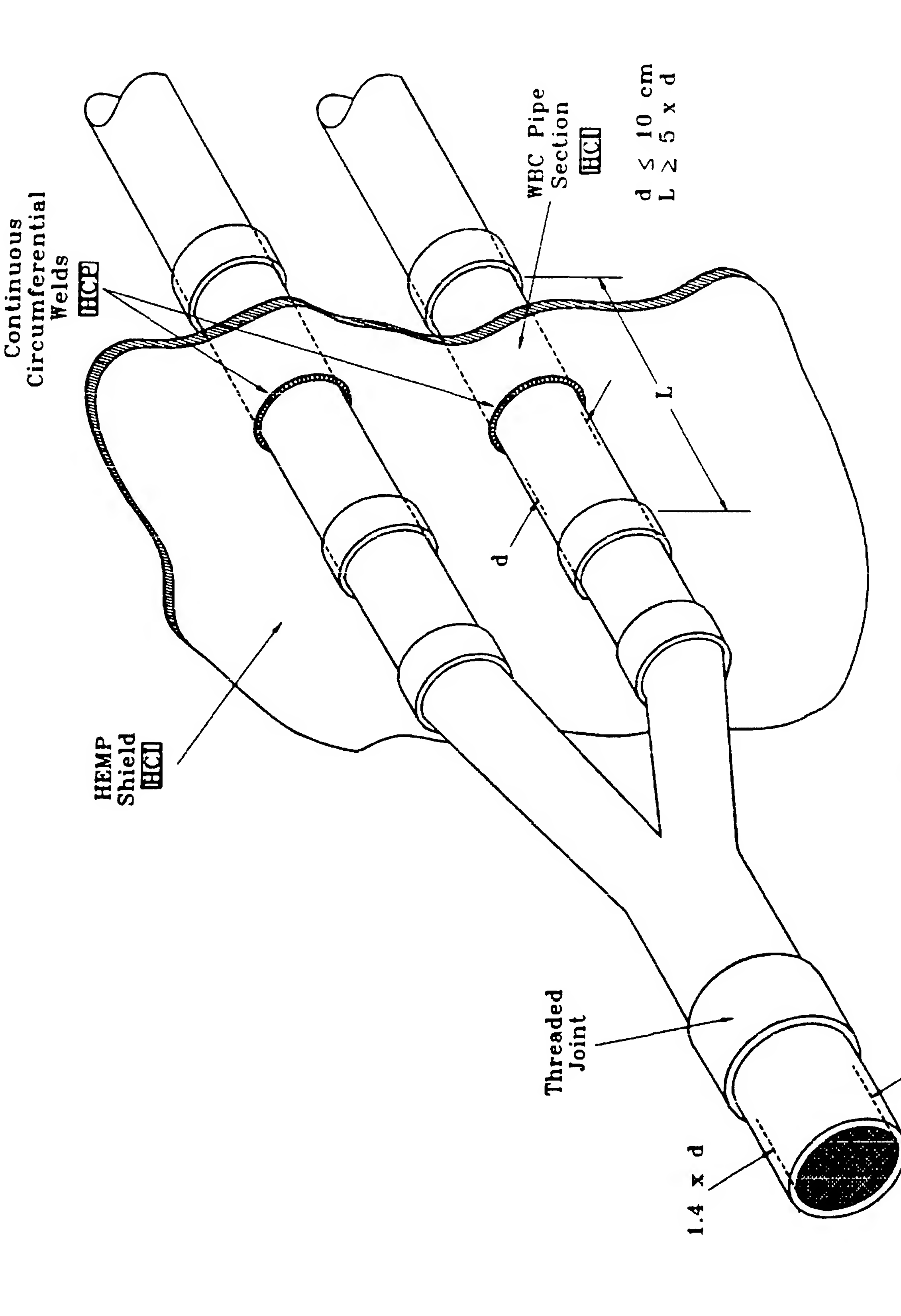
FIGURE 139. Shield-within-a-shield.

188-125, then special protective measures must be implemented to harden the affected equipment.

The design process is somewhat simplified when the deficiency is discovered through verification testing. The environments and coupling tasks are unnecessary, since residual internal stresses have already been measured. An evaluation of the equipment must then be done to understand why these relatively small levels of excitation caused upset or damage. The necessary remedial modifications will be determined from results of this assessment. The standard offers a broad spectrum of methods that may be employed for this purpose.

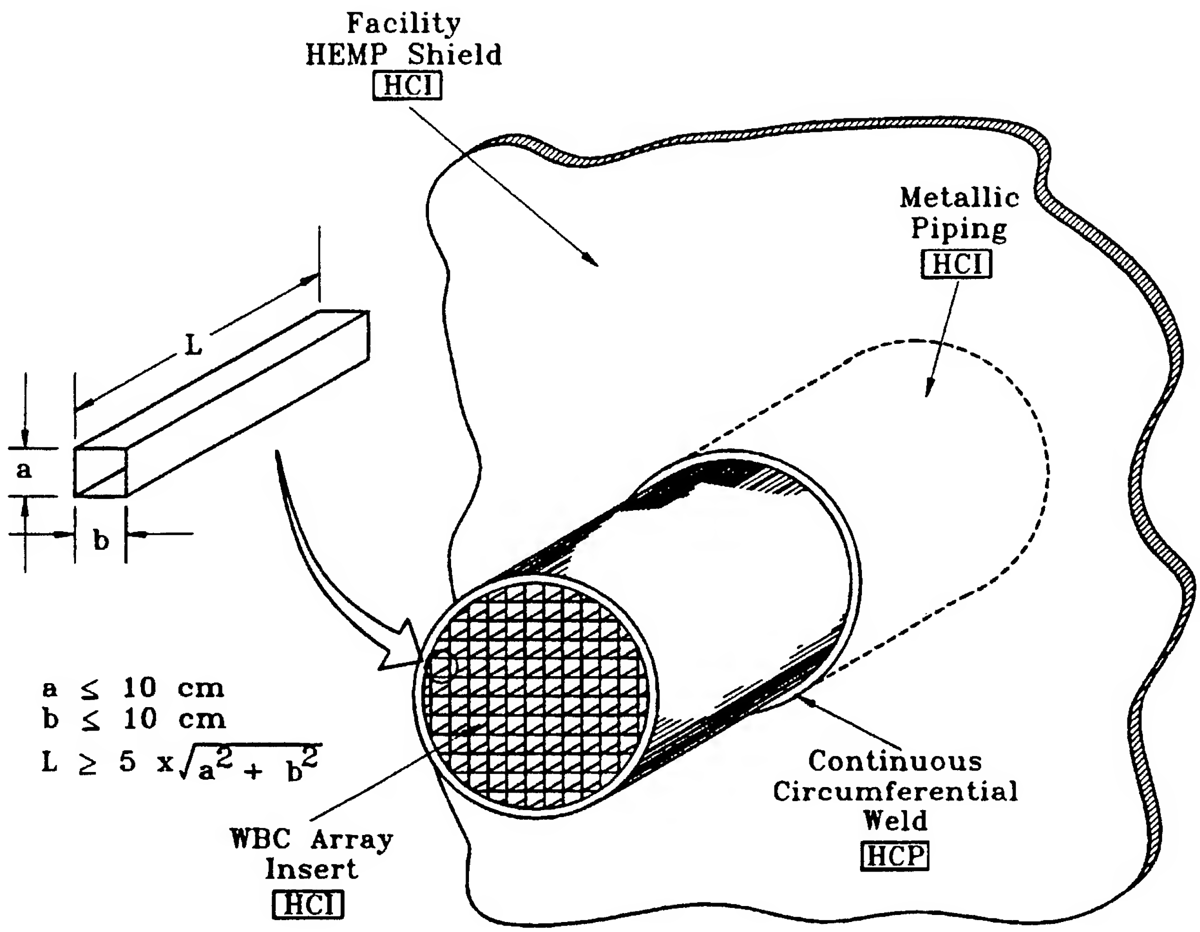
14.3.5 Special protective barrier design and construction.

14.3.5.1 Special protective barriers for piping POEs. It should be possible to eliminate waveguide-below-cutoff piping penetrations larger than 10 cm (4 in) inside diameter in almost all cases, including generator and boiler exhaust stacks and sewage lines. Figure 140 illustrates two principal methods for achieving this goal. In figure 140a, two 10-cm pipes are provided to permit approximately the same fluid flow rate with the same



a. Multiple pipe penetrations.

FIGURE 140. Techniques for eliminating oversized piping penetrations.



b. Waveguide-below-cutoff array pipe penetration.

FIGURE 140. Techniques for eliminating oversized piping penetrations (continued).

pressure drop as a single pipe with an inside diameter of 14 cm. Three, four, or more tubes in parallel can replace even larger pipes. The waveguide-below-cutoff array piping penetration protection device, figure 140b, is an approach identified in MIL-STD-188-125. Each of the individual cells in the array must satisfy the maximum cross-section and minimum length requirements of the standard, and there must be continuous electrical bonds at the cell wall intersections and between the cell walls and the WBC pipe section. Section 10 presents array construction methods.

In the rare circumstance where avoidance is not possible (i.e., the fluid contains solids larger in dimension than 10 cm), a special protective barrier must be established. The barrier approach using a separate shield with protected penetrations is allowable, but seldom cost effective. The alternate technique is to maintain a closed metal piping system within the protected volume. The requirements for a closed system of piping[5] as a special protective barrier are as follows:

a. The pipe walls must be metallic.

b. rf continuity must be maintained at all couplings in the piping system, using welded or threaded joints or rf-gasketed flanges.

c. Electromagnetic closure covers must be provided and installed when the oversized piping system is opened for maintenance.

14.3.5.2 Special protective barriers for electrical POEs. The preceding paragraph noted that the designer is almost always able to avoid special protective volumes due to oversized pipe penetrations. Unfortunately, an equivalent statement cannot be made with respect to electrical POE protective devices that cannot achieve transient suppression/ attenuation performance prescribed for primary barrier elements. In fact, the need for a special protective volume and barrier enclosing a radio transmitter or transceiver is likely to be the rule rather than the exception. Elimination of this special design requirement will normally be possible for all other classes of electrical POEs, however.

MIL-STD-188-125 identifies two approaches for implementing a special protective barrier. The drawing reproduced from the standard in subsection 14.2 shows a radio transmitter located inside a separate shield with protected penetrations. The alternative, schematically illustrated by figure 141, constructs the special protective barrier using the antenna cable shield or conduit and transmitter/transceiver cabinet. This second option

[5]Any branch of the metal piping that is less than 10 cm in inside diameter, at least five diameters in length, and does not have an interior dielectric lining is considered to close the system. Metallic walls and rf continuity at joints are not required in extensions beyond this point.

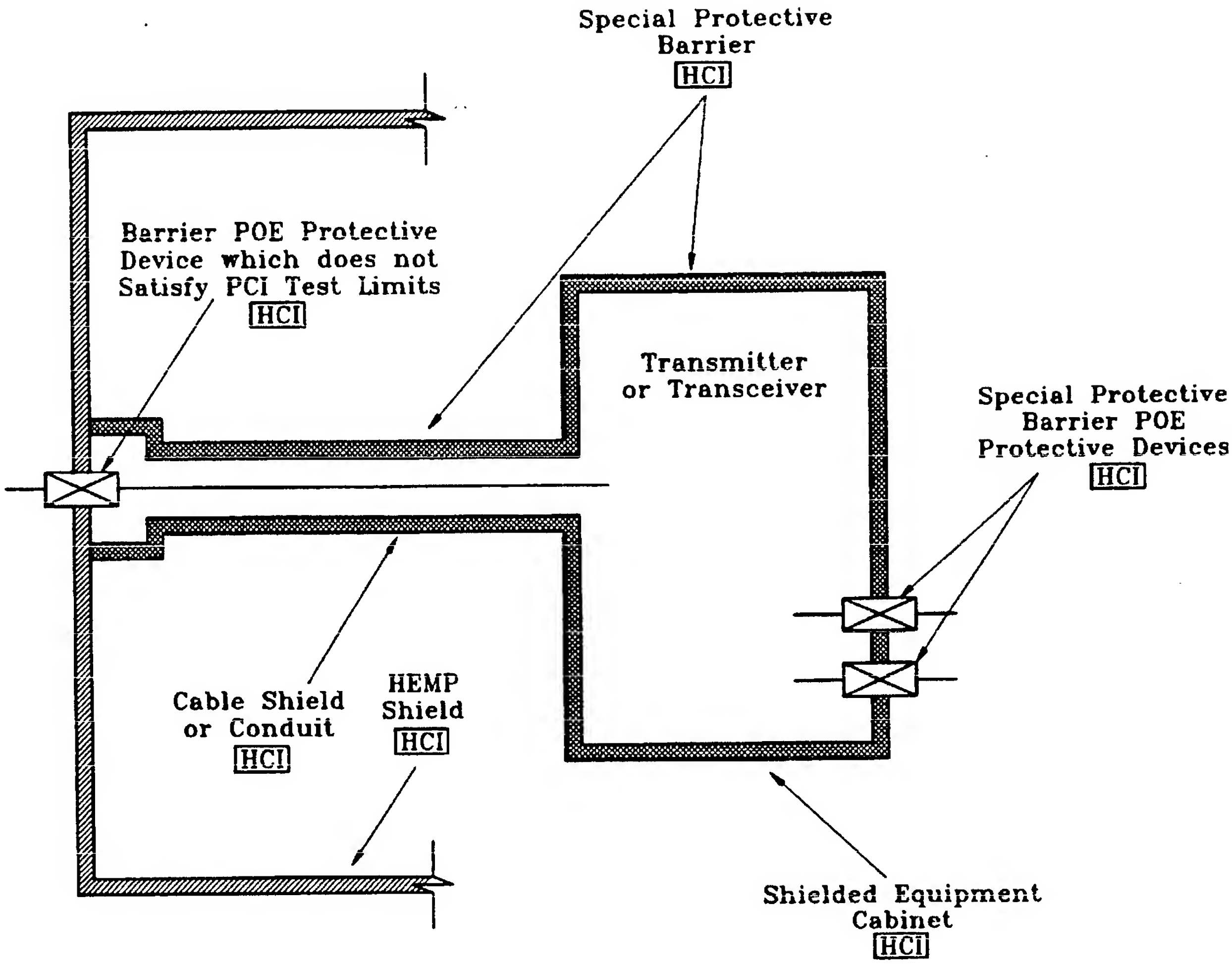


FIGURE 141. Special protective barrier constructed with cable and equipment cabinet shields.

becomes cost competitive when the equipment rack is well-shielded for electromagnetic compatibility purposes.

Performance requirements for the special shield and penetration treatments are those necessary to prevent electromagnetic contamination of the protected volume environment. Stresses in the special protective volume will be dominated by the transient entering through the barrier device which does not satisfy the PCI test limits. The special protective shield must be of sufficient quality that shielding effectiveness measured through the combined primary and special protective barriers meets the facility requirements. Similarly, the special protective barrier electrical POE protective devices must be designed so that transient suppression/attenuation through the combination of the two barriers satisfies PCI test criteria.

14.3.5.3 Hardening mission-essential equipment in a special protective volume. Since electromagnetic stresses in a special protective volume exceed the "benign" values allowed in the protected volume, the ability of the enclosed equipment to withstand the larger transients must be assessed.

The environment is determined by measuring or predicting leakage through the POE protective device or devices responsible for creating the special protective requirement. Since the region is inside the HEMP shield, this would typically be the dominant source of excitation on other conductors. The coupling determination involves propagation of this signal through equipment circuits. Comparison of induced stresses with the equipment vulnerability threshold estimates will indicate whether additional hardening is necessary to achieve the required 20 dB margin of safety for conducted transients. An appropriate design can then be developed.

Because the requirement to establish a special protective volume often results from an electrical POE protective device connected to a high-power equipment interface, additional hardening is not always needed in these situations since high-power equipment may be inherently more robust.

14.3.6 Fielded system examples. A satellite communications antenna was originally designed and fielded in a non-HEMP hardened configuration. When HEMP survivability requirements were later levied on facilities using this equipment, a HEMP hardening upgrade program was undertaken, and special protective measures were implemented.

Figure 142 illustrates the modified antenna, including a topological outline of the structural shield created in the retrofit hardening process. This was accomplished by

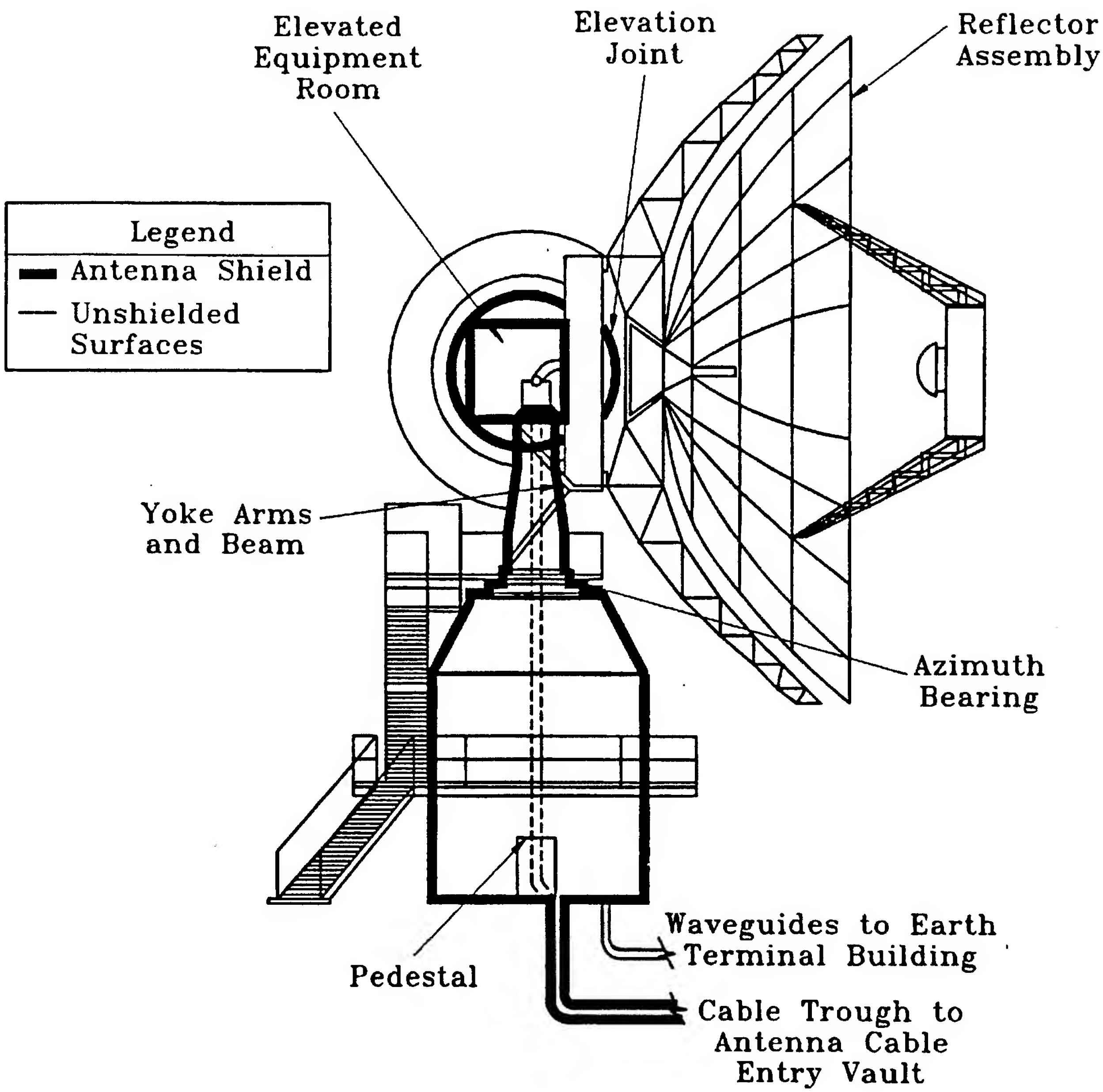


FIGURE 142. Satellite antenna and antenna structural shield.

installing a welded steel liner inside the concrete pedestal structure and making the following additional changes:

a. Pedestal and elevated equipment room doors were replaced with shielded doors.

b. Azimuth and elevation joints were modified to provide electromagnetic closure.

c. Corrosion-resistant steel flashings were welded across mechanically fastened joints (pedestal to conic section, conic section to azimuth bearing, azimuth bearing to yoke/beam assembly, splice joints in the yoke arms, and the yoke interface to the elevated equipment room).

d. Waveguide-below-cutoff array panels were provided at all ventilation openings, and yoke access covers were modified to provide rf closure.

Electrical penetrations of the structural shield were protected by surge arresters and/or filters, and shielded cable penetrations were circumferentially bonded. Additionally, the open cable trough from the antenna to the earth terminal building was replaced with a welded rigid steel conduit.

Mission-essential components that remained outside the antenna structural shield included the antenna feed horn and the elevation drive motors and position sensors. Design studies concluded that these elements required no additional protection, because the associated cabling was shielded and the components themselves were relatively robust. This finding was later confirmed in a facility verification test.

It needs to be noted that the retrofit HEMP protection for the satellite antenna was designed before the first draft of MIL-STD-188-125 was started. Nevertheless, nearly all mission-critical systems have been enclosed within a shielded topology, and only a few motors and sensors remain outside the barrier. The attainable shielding effectiveness was limited by a major design feature that could not practically be replaced. If a new antenna subsystem of this type was being developed subsequent to the publication of MIL-STD-188-125, the antenna structural shield would be required to satisfy the 100 dB (nominal) criteria. Furthermore, most of the motors and sensors would be placed inside the barrier, and few SPMs would be employed.

Many other examples of the use of special protective measures can be found at existing facilities. At some sites, commercial computers are installed within an approximately 40 dB (nominal) shield that is inside the 100 dB (nominal) electromagnetic barrier. Some waste heat radiators are enclosed by screened shields. External motors with conduit-protected power and control wiring and surge arresters installed on their terminals are common. The

satellite antenna program described above, however, probably represents the most difficult special case encountered to date.

14.4 References.

14-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

14-2. "Military Standard - High-Altitude Electromagnetic Pulse (HEMP) Environment (U)," DoD-STD-2169 (effective), Dept. of Defense, Washington, DC (S).

14-3. "Electromagnetic Pulse Interaction Notes," AFWL EMP 3 Series, Phillips Laboratory, Kirtland AFB, NM, AFWL EMP 3-1.

14-4. Vance, E. F., "Electromagnetic-Pulse Handbook for Electric Power Systems," DNA 2466F, Defense Nuclear Agency, Washington, DC, 4 February 1975.

14-5. "DNA EMP Engineering Handbook for Ground-Based Facilities," DNA-H-86-60, Defense Nuclear Agency, Washington, DC, 15 November 1986.

14-6. Wunsch, D. C., and R. R. Bell, "Determination of the threshold failure levels of semiconductor diodes and transistors due to pulse power voltages," *IEEE Trans. Nuc. Sci.* NS-15, No. 6, pp. 244-259, December 1969.

14-7. Alexander, D. R., R. M. Turfler, and J. R. Barnum, "Subsystem Malfunction Investigations Report," AFWL-TR-85-134-PT-1 and -PT-2, Phillips Laboratory, Kirtland AFB, NM, April 1985.

15. CORROSION CONTROL

15.1 Basic principles. Corrosion plays a major role in the long-term reliability and life-cycle cost of a HEMP protection subsystem, and control of corrosion is an important consideration. Corrosion is the deterioration of a material, usually a metal, because of reactions with its environment and other materials in the vicinity. In simplest terms, corrosion is the tendency of metals to return to their natural state (ores).

A convenient classification system for corrosion is based on the visual appearance of the corroded metal. This classification system contains eight mechanisms of corrosion. Some of these mechanisms are unique, but all of them are somewhat interrelated. The mechanisms are uniform or general attack; crevice corrosion; pitting; intergranular corrosion; selective leaching or parting; erosion corrosion; stress corrosion; and galvanic or two-metal corrosion. See MIL-HDBK-729 (reference 15–1) for additional information.

These eight mechanisms can be grouped into two broad categories—general and localized corrosion. Uniform attack and selective leaching are examples of general corrosion. Crevice and intergranular corrosion are examples of localized corrosion. General corrosion affects the entire metal surface; localized corrosion affects a very small area or volume. General corrosion is typically readily visible, while localized corrosion is not. This makes localized corrosion the most difficult type of corrosion to detect and control. Localized corrosion can lead to failures such as failure of structural components or pitting holes in conduits and sheets. Because general corrosion affects large areas, it tends to inhibit localized corrosion. Thus, if general corrosion is present, the likelihood of localized corrosion also being present is extremely low.

15.1.1 Uniform attack. Uniform attack is the most common form of corrosion. It is normally characterized by a chemical or electrochemical reaction that takes place uniformly over the entire exposed surface or over a large area. The metal becomes thinner and eventually fails.

Uniform corrosion can be prevented or reduced by the use of proper treatments including coatings, inhibitors, and cathodic protection.

15.1.2 Crevice corrosion. Crevice corrosion is the severe localized corrosion that often occurs within crevices and other confined areas on metal surfaces exposed to corrosives. This form of corrosion is usually associated with small volumes of stagnant solution caused by holes, gasket surfaces, lap joints, surface deposits, and crevices under bolt and rivet heads. Examples of deposits that may produce crevice corrosion are sand, dirt, commercial

corrosives, and other solids. The deposit itself acts as a shield and creates a stagnant area beneath itself. Contact between metal and a nonmetallic surface, such as a gasket, can cause crevice corrosion.

Methods and procedures for combating or minimizing crevice corrosion include:

a. Use welded joints instead of riveted or bolted joints in new equipment. Quality welds and complete penetration are necessary to avoid porosity and crevices on the inside (if welded only from one side).

b. Close crevices in existing lap joints by continuous welding, caulking, or soldering.

c. Design for complete drainage; avoid sharp corners and stagnant areas.

d. Inspect and remove deposits frequently.

e. Maintain a noncorrosive environment.

f. Use 'solid" nonabsorbent gaskets, such as Teflon, wherever possible.

15.1.3 Pitting. Pitting is a form of extremely localized attack that results in holes in the metal. Generally, a pit may be described as a cavity or hole with the surface diameter about the same or less than the depth. Pits usually grow in the direction of gravity. Most pits develop on horizontal surfaces and grow downward. Pitting usually requires an extended initiation period before becoming visible. This period varies from months to years. Once started, however, a pit penetrates the metal at an ever-increasing rate. From a practical standpoint, most pitting failures are caused by chloride and chlorine-containing ions. The methods suggested for combating crevice corrosion generally also apply for pitting.

15.1.4 Intergranular corrosion. Intergranular corrosion is a localized attack at and adjacent to grain boundaries—the boundaries between crystalline arrays produced when a metal solidifies-with relatively little corrosion of the grains. This causes the alloy to lose its strength and possibly disintegrate. Intergranular corrosion can be caused by impurities at the grain boundaries, enrichment of one of the alloying elements, or depletion of one of these elements in the grain boundary areas. For example, depletion of chromium in the grain boundary area results in intergranular corrosion of stainless steels. Prevention of intergranular corrosion consists of minimizing the elemental inhomogeneities at the grain boundaries.

15.1.5 Selective leaching or parting. Selective leaching or parting is the removal of one element from a solid alloy by corrosion processes. The most common example is the selective removal of zinc in brass alloys (dezincification). Dezincification is readily observable in common yellow brass because the alloy assumes a red or copper color that contrasts with the original yellow. Dezincification can be minimized by reducing the amount of oxygen in the environment, by cathodic protection, or by using a less susceptible alloy.

15.1.6 Erosion corrosion. Erosion corrosion is the acceleration of deterioration or attack on a metal because of relative movement between a corrosive fluid and the metal surface. Generally, this movement is quite rapid, and mechanical wear effects or abrasion are involved. Metal is removed from the surface as dissolved ions, or it forms solid corrosion products that are mechanically swept from the metal surface.

Four methods for the prevention or minimization of damage due to erosion corrosion are used. They are implementing materials with better resistance to erosion corrosion; designing the system or altering the system environment to prevent the occurrence of erosion corrosion; applying coatings; and implementing cathodic protection.

15.1.7 Stress corrosion. Stress-corrosion cracking refers to cracking caused by the simultaneous presence of tensile stress and a specific corrosive medium. During stress-corrosion cracking, the metal or alloy is virtually unattached over most of its surface, while fine cracks progress through it. This phenomenon has serious consequences, since it can occur at stresses within the range of typical design stress. Although stress corrosion represents one of the most important corrosion problems, the mechanism involved is not well understood due to the complex interplay of metal, interface, and environmental properties.

Because the mechanism of stress-corrosion cracking is not well defined, methods of preventing this type of corrosion are either general or empirical in nature. The methods include:

a. Lowering the stress below the threshold value, if one exists

b. Eliminating the critical environmental species by, for example, degasification, demineralization, or distillation

c. Changing the alloy, if neither the environment nor stress can be changed

d. Applying cathodic protection to the structure

e. Adding inhibitors to the system, if feasible

f. Applying coatings to prevent the corrosive environment from contacting the metal

15.1.8 Galvanic or two-metal corrosion. Galvanic coupling is the creation of a voltage potential difference between two dissimilar metals in a corrosive or conductive solution. If these metals are placed in contact or otherwise electrically connected, this potential difference produces electron flow between them. This flow of electrons increases the corrosion of the more active metal. This form of electrochemical corrosion is called galvanic corrosion. The term "anode" describes the metal surface being corroded and from which the current leaves; the term "cathode" describes the metal surface that collects the current. Usually the cathode corrodes very little or not at all.

Metals and metal alloys can be arranged in a list based on their voltage potential. This list, called a galvanic series, is illustrated in table XII. When two metals are in electrochemical contact, the metal closer to the cathodic end of the galvanic series will experience less corrosion. For example, if zinc and steel are in contact, the zinc will behave as an anode, corroding and thereby inhibiting corrosion of the steel. If steel and copper are in contact, however, the steel behaves as an anode. The farther apart the metals are in the series, the higher the electromotive force between them and the higher the corrosion rate will be.

A number of procedures or practices can be used for combating or minimizing galvanic corrosion. One procedure may in some cases be sufficient, but sometimes a combination may be required. These practices include:

a. Select combinations of metals as close together as possible in the galvanic series. Mounting hardware and fasteners such as pipe hangers and bolts must be galvanically similar to the interfacing metal parts or must be insulated from them.

b. Avoid the unfavorable area effect of a small anode and large cathode. Small parts such as fasteners sometimes work well for holding less resistant materials.

c. Insulate dissimilar metals whenever practicable. It is important to insulate completely if possible. For example, the shank of a bolt used to connect two insulated, dissimilar metals must also be insulated.

d. Apply coatings with caution. If one of two dissimilar metals in contact is to be coated, the cathodic metal should be coated. Keep the coatings in good repair—particularly the one on the anodic metal.

e. Add inhibitors, if possible, to decrease the aggressiveness of the environment.

TABLE XII. Galvanic series of common metals and alloys.

Magnesium	ANODIC OR MOST ACTIVE
Magnesium Alloys	
Zinc	
Galvanized Steel or Iron	
1100 Aluminum	
Cadmium	
2024 Aluminum	
Mild Steel or Wrought Iron	
Cast Iron	
Chromium Steel (active)	
Ni-Resist (high-Ni cast iron)	
18-8 Stainless Steel (active)	
18-8 Mo Stainless Steel (active)	
Lead-tin Solders	
Lead	
Tin	
Nickel (active)	
Inconel (active)	
Hastelloy B	
Manganese Bronze	
Brasses	
Aluminum Bronze	
Copper	
Silicon Bronze	
Monel	
Silver Solder	
Nickel	
Inconel	
Chromium Steel	
18-8 Stainless Steel	
18-8 Mo Stainless Steel	
Hastelloy C	
Chlorimet 3	
Silver	
Titanium Graphite	
Gold	
Platinum	CATHODIC OR MOST NOBLE

f. Avoid threaded joints for materials far apart in the series. Much of the effective wall thickness of the metal is cut away during the threading process. In addition, spilled liquid or condensed moisture can collect and remain in the thread grooves. Brazed joints are preferred, using a brazing alloy more cathodic than at least one of the metals to be joined. Welded joints using welds of the same alloy are even better.

g. Design for the use of readily replaceable anodic parts or make them thicker for longer life.

h. Install a third metal that is anodic to both metals in the galvanic contact.

See reference 15–2 for more detailed discussions on these topics.

15.1.9 Facility corrosion protection methods. A summary of the corrosion prevention and protection methods applicable to fixed, ground-based facilities is provided below.

a. Altering or modifying the environment containing the corrosive elements
   - Use of an HVAC system to control humidity
   - Dehumidifiers
   - Isolation from salt spray

b. Proper selection of corrosion-resistant materials (reference 15-2)
   - Use of stainless steel (but not underground unless catholically protected, and not in contact with galvanized or plain carbon steel)
   - Use of electrochemically compatible materials

c. Application of a barrier coating or paint that separates the electrolyte from potential galvanic couples

d. Reversing galvanic action by cathodic protection
   - Sacrificial anodes
   - Direct current applied to counteract galvanic current

e. Coating plus cathodic protection for underground environments

15.2 MIL-STD-188-125 requirements.

> 5.1.12 Corrosion control. Corrosion protection measures shall be implemented in the design and construction of the HEMP protection subsystem. The facility shield and POE protective devices shall be constructed with inherently corrosion-resistant materials or metals shall be coated or metallurgically processed to resist corrosion. Pockets where water or condensation can collect shall be avoided and a crawl space shall be provided above the ceiling shield to allow inspection for roof leakage. Buried conduits or cables shall be coated with asphalt compound, plastic sheaths, or equivalent corrosion protection, and a means for detecting leakage shall be provided. Joints between dissimilar metals shall be avoided and, where required, shall be provided with corrosion preventive measures. Cathodic protection shall be provided, where required by environmental conditions.

15.3 Applications.

15.3.1 Metals and their corrosion characteristics. The following discussions are taken heavily from reference 15–2. See this reference and reference 15–3 for more detailed discussions of metals and their corrosion characteristics.

15.3.1.1 Iron and iron alloys.

15.3.1.1.1 Cast irons. Cast iron is a generic term that applies to high-carbon iron alloys containing silicon. The common alloys are designated as gray cast iron, white cast iron, malleable cast iron, ductile or nodular cast iron, and high-silicon cast iron. All but the latter have poor corrosion resistance.

High-silicon cast iron is produced by increasing the silicon content of gray cast iron to over 14 percent. High-silicon cast iron is extremely corrosion resistant to many environments. The excellent corrosion resistance is due to formation of a passive silicon oxide surface layer that forms during exposure to the environment. They are used extensively as anodes for impressed current cathodic protection.

In addition to silicon, molybdenum, nickel, and chromium are added to cast irons for improved corrosion and abrasion resistance, heat resistance, and improved mechanical properties. Copper additions impart better resistance to sulfuric acid and atmospheric corrosion.

15.3.1.1.2 Carbon steels and irons. Hardness and strength of steels depend largely on their carbon content and heat treatment. Carbon content has little if any effect on general corrosion resistance of these steels in most cases.

Wrought iron is a "mechanical" mixture of slag and low-carbon steel. Many claims of better corrosion resistance are made, but each proposed application should be carefully evaluated to be sure the extra cost over ordinary steel is justified.

Iron is alloyed, singly or in combination, with carbon, chromium, nickel, copper, molybdenum, phosphorus, sulfur, and vanadium in the range of a few percent to produce low-alloy steels. The higher alloy additions are usually for better mechanical properties and hardenability. The lower range of about two percent maximum is of great interest from the corrosion standpoint. Strengths are appreciably higher than plain carbon steel, but the most important attribute is better resistance to atmospheric corrosion.

15.3.1.1.3 Stainless steels. Stainless steels were specifically developed to increase corrosion resistance. Chromium is the main alloying element, and the steel should contain at least 11 percent. Chromium is a reactive element, but it and its alloys passivate and exhibit excellent corrosion resistance to many environments.

Stainless steels can be divided into four groups. Group III steels are the most widely used, with II, I, and IV following in order. The American Iron and Steel Institute and Unified Numbering System numbers of several of the more common types are listed in table XIII.

Group I steels are called martensitic stainless steels because they can be hardened by heat treatment similar to ordinary carbon steel. Strength increases and ductility decreases with increasing hardness. Corrosion resistance is usually less than that found in groups II and III. Corrosion resistance is generally better in the hardened condition than in the annealed or soft condition.

Group II ferritic, nonhardenable steels are so named because they cannot be hardened by heat treatment. Ordinary carbon steels harden because of phase changes when cooling. These steels are austenitic at higher temperatures. Austenite is gamma iron, is nonmagnetic, and has a face-centered cubic lattice. Upon cooling, it transforms to alpha iron or ferrite, which is magnetic and body-centered cubic. When cooled rapidly, it becomes hard, brittle martensite, which is magnetic but has a body-centered tetrahedronal lattice. Group I steels are magnetic and are hardenable. Type 405 should be included in group 1, but since it does not harden because of aluminum content, it is included in group II

TABLE XIII. Common types of stainless steels.

Type	Number
Group I - Martensitic Chromium Steels	
410	S 41000
416	S 41600
420	S 42000
431	S 43100
440A	S 44002
Group II - Ferritic, Nonhardenable Steels	
405	S 40500
430	S 43000
442	S 44200
446	S 44600
Group III – Austenitic Chromium-Nickel Steels	
201	S 20100
202	S 20200
301	S 30100
302	S 30200
302B	S 30215
304	S 30400
304L	S 30403
308	S 30800
309	S 30900
309S	S 30908
310	S 31000
310S	S 31008
314	S 31400
316	S 31600
316L	S 31603
317	S 31700
321	S 32100
347	S 34700
Alloy 20	J 95150
Group IV – Age-Hardenable Steels	
322	—
PH 13-8 Mo	S 13800
17-4 PH	S 17400
17-7 PH	S 17700
AM-350	S 35000
CD-4MCu	—

Type 430 can be readily formed and has good corrosion resistance to the atmosphere. It is used in the production, transport, and storage of nitric acid.

One of the most interesting aspects of the group II steels is their resistance to stress corrosion. They do quite well where the more common steels fail, particularly in chloride-containing waters.

Recently developed ferritic, nonhardenable stainless steels containing very low amounts of carbon and nitrogen are commercially available. High purity is attainable through advanced steel-making technologies. The obvious advantage of these ferritic steels is resistance to stress-corrosion cracking in chloride environments, where they are far superior to the austenitic stainless steels such as types 304 and 316. Pitting resistance is also better for the former. Welding of high-purity, ferritic stainless steels must be done properly and carefully in inert atmospheres to avoid contamination and embrittlement.

Group III austenitic stainless steels are essentially nonmagnetic and cannot be hardened by heat treatment. Like the ferritic steels, they are hardenable only by cold-working. Most of these steels contain nickel as the principal austenitic former, but the newer ones like types 201 and 202 contain less nickel and substantial amounts of manganese. The austenitic steels possess better corrosion resistance than the straight chromium steels (groups I and II) and generally have the best resistance of any of the four groups. For this reason, austenitic steels are widely specified for the more severe corrosion conditions. They are rust-resistant in the atmosphere and find wide use in architectural applications.

Types 201 and 202 show about the same corrosion resistance as the type 302 grade. The most commonly used types are 304, 304L, 316, and 347. The molybdenum-bearing steel, type 316, is considerably better in many applications than type 304. Type 316 exhibits much better resistance to pitting, sulfuric acid, and organic acids. Corrosion resistance and heat resistance generally increase with nickel and chromium contents. For instance, type 310 is one of the better heat-resistant alloys.

The L-grade, e.g. 304L, stainless steels are steels that have an extra-low carbon (less than 0.03 percent carbon) content. This carbon content is the maximum amount that is soluble in stainless steels and does not easily come out of solution. L-grade stainless steels were developed to decrease their susceptibility to intergranular corrosion due to welding.

Group IV consists of the age-hardened or precipitation-hardened steels. They are hardened and strengthened by solution-quenching, following heating for long times at high temperatures. Corrosion resistance to severe environments is generally less than for

group III, except for CD-4MCu which is very much better than the other five listed. It is also superior to many of the group III steels.

The relative permeability of a stainless steel alloy should not be a deciding factor in choosing stock for HEMP shielding; any stainless steel of construction thickness will have adequate shielding effectiveness.

15.3.1.1.4 Welding and stainless steels. The chromium constituent in stainless steel is primarily responsible for the stain and corrosion resistance of these steels. It has an affinity for oxygen and forms a thin, impervious, protective oxide layer. Chromium also has an affinity for carbon and forms chromium carbides rapidly between 425 and 870°C (800-1600°F).

When chromium carbides are formed, they tie Up much of the chromium and severely reduce the corrosion resistance of the steel. Typically, this can happen in a zone next to the weld joint. This phenomenon, known as sensitization, occurs because a region next to the weld is heated to 425—870°C (800-1600°F). If the weld joint is subjected to a corrosive environment, knife-line attack (a form of intergranular corrosion) results. Three techniques are used to mitigate sensitization. These methods can be expensive and should be used only when sensitization is a problem.

a. Extra-low carbon grades of steel, e.g. 304L, and filler material should be used and must be specified for field welds unless effective post-weld heat treatments can be used.

b. Stabilizing elements such as columbium and tantalum can be used. These form carbides preferentially over chromium, thereby tying up the carbon.

c. A post-weld heat treatment can be used. The most common heat treatment technique is to solution-anneal at 104O°C (1900°F), then water-quench. This technique puts all the carbon in solution and keeps it there by rapidly cooling through the 870-425°C (1600-800°F) range. Post-weld heat treatments cannot be accomplished reliably in the field and generally are not recommended because the cooling process is difficult to control.

15.3.1.2 Copper and its alloys. Copper differs from most other metals in that it combines corrosion resistance with high electrical and heat conductivity, and strength when alloyed, except at high temperatures. Copper exhibits good resistance to urban, marine, and industrial atmospheres and waters. It is not corroded by acids unless oxygen or other oxidizing agents are present. Reduction of oxygen to form hydroxide ions is the predominant cathodic reaction for copper and its alloys. Copper-based alloys are resistant

to neutral and slightly alkaline solutions, with the exception of those containing ammonia which causes stress corrosion and sometimes rapid universal attack.

Copper is little affected by lime or solutions of calcium hydroxide such as in fresh or hardened concrete. Chloride admixtures should be avoided where copper and concrete are to be in contact, especially if they are exposed to moisture.

Copper and brasses are subject to erosion corrosion. The bronzes and aluminum brass are much better in this respect. The bronzes are stronger and harder. The cupronickels, with small iron additions, are also superior in erosion-corrosion resistance.

Copper and its alloys rarely suffer galvanic corrosion as a result of contact with other metals, but often cause corrosion of more anodic metals such as steel and galvanized steel. Their position in the galvanic series shows that copper and its alloys are cathodic to common structural metals.

15.3.2 Environmental control. Minimum exposure of the shield surfaces to the outside air or soil is desirable. From a corrosion standpoint, the shield should form an inner wall between the exterior structural wall and the interior finished wall. Aside from improving the lifetime integrity of the shield, thinner and thus less costly material can be used. MIL-STD-188-125 (reference 15-4) requires a crawl space above the ceiling shield for inspection access. It is also recommended that access be provided to both sides of the shield wall and interior floor components to permit visual inspection and required HM/HS activities.

Moisture can migrate through concrete and cause the shield to corrode. In some existing facilities, insulation in contact with the shield has trapped moisture and has led to early failure of the shield. In all cases, the penetration entry area should be readily accessible for inspection, and should be designed so that the facility HVAC system can help minimize condensation and corrosion in this area. Weather seals, vapor barriers, ventilation, space heating, and desiccants should be employed as necessary to keep the shield and the PEA dry. Corrosion can be virtually eliminated by the proper selection of materials, methods of construction, corrosion-control treatments, and by the use of cathodic protection techniques and environmental seals. From past experience, it appears that all of these add very little to the overall initial cost and yet can greatly reduce maintenance support costs.

The design of the HEMP protection system must take into consideration potential sources of excessive moisture. Leaky roofs and leaky water pipes have caused corrosion of shields. Water fountains inside shielded enclosures have caused corrosion because of leaks

and splashing water. Condensation where chilled water pipes and HVAC ducts penetrate a shield has been a source of corrosion. The design of the HEMP shield penetrations must provide insulation, thermal barriers, or other means to prevent condensation from forming on either side and deteriorating the HEMP barrier.

15.3.3 Material selection. Material corrosion is strictly a property of the environment. A material that will survive in one environment may corrode in another. With time, the environment may change. This change may even go unnoticed (e.g. leaching of salt into the soil). Therefore, the environment must be considered when choosing a material.

Of the shield materials allowed by MIL-STD-188-125, stainless steel is somewhat more resistant to corrosion than copper or galvanized steel, and certainly more than low-carbon steel. Stainless steels with a minimum of 16 percent chromium and 8 percent nickel (18-8) have the best long-term corrosion resistance of any of the stainless steels. L-grade stainless steels are recommended for welding because their corrosion-resistant properties are not easily lost through welding. Galvanized steel has numerous associated problems, including removal of the galvanizing prior to welding, health risks, and refinishing of welded areas. The use of galvanized steel sheets, because of these disadvantages, is recommended in relatively few cases. Reference 15–5 can provide guidance on the advisability of using galvanized steel.

For below-grade penetrations (e.g. water, sewer, power conduits, fuel), the problems of corrosion control may be more difficult. Electrolytic corrosion can take place between dissimilar metals underground or chemically active soil can attack the metals. The effect can be either to degrade the HEMP-related metals (shield, ground rods, electrical bonds) or to attack the existing utility conductors (water, sewer, power conduit, fuel). In either case, the result is a maintenance problem, and the HEMP failures might go undetected for an appreciable time. When dissimilar metals are used underground, coatings should always be supplemented by cathodic protection. For numerous reasons, below-grade penetrations should be avoided wherever possible.

15.3.4 Cathodic protection. In general, cathodic protection can be used on buried or submersed metals to inhibit corrosion. In those cases where portions of the HEMP shield are below grade, where many ground rods are used, or where an extensive buried ground plane is used, a cathodic protection system should be considered. Note that a cathodic protection system only works for surfaces which are exposed to an electrolyte; therefore, only the outside surface of a below-grade shield can be protected catholically. Either a passive system using a sacrificial anode or an active electrical (impressed current) method may be employed (see MIL-HDBK-1004/10, reference 15-6). The anodes in the active system are metals that are biased with a positive electrical potential relative to

the conductors to be protected. With proper design, this technique can assure at least a 20-year life of the below-grade metals and their associated bonds to the facility shield. See MIL-HDBK-1004/10 for more information on corrosion and design of cathodic protection.

15.3.5 Corrosion protection with a barrier coating. Coatings are commonly used to prevent or guard against corrosion. There are many types of coatings, as sampled below:

a. Conversion coatings (inorganic)

b. Anodizing

c. Aluminizing

d. Phosphatizing

e. Oxide coatings

f. Metallic coatings (such as galvanizing with zinc)

g. Zinc chromate

h. Organic coatings

i. Paints

j. Enamels

k. Varnish

l. Lacquers

m. Primers

Much of the material directly above has been taken from reference 15-1, and that document contains details of the application, assembly, and maintenance of metals and coatings to minimize corrosion effects. Factory- and shop-applied coatings are generally more effective than field-applied coatings. Some construction processes such as welding, however, will often remove existing coatings. Other needs such as bonding may also require that the coating be removed. Provisions must be made to restore the protection, if the coating is removed. Further information on metal finishes and coatings may be found in MIL-STD-1516, reference 15-7.

15.3.6 Corrosion protection of bonds. As discussed in section 13, the proper functioning of the electrical bonds on penetrations can be critical to HEMP survivability. Thus, every effort should be made to maximize the life of such bonds. Welded or brazed bonds are preferred because they are the least likely to degrade with time, especially if protected from moisture. Clamping techniques are less desirable because of the possibility of corrosion in the joint, but even these can have an extended life if corrosion inhibitors (coatings) are used in the joint and are properly cured.

The use of a sealant around the edge of joints or bonds to exclude moisture has not worked well, since most sealants have a limited life and are often difficult to evaluate. Aged sealants tend to harden, shrink, crack, and disintegrate. Many such joints are hard to reach for repair. Where a sealant must be used, a polysulfide sealant is recommended.

15.3.7 Corrosion control plan. A corrosion prevention and control plan, as described in MIL-STD-1568 (reference 15–8), should be prepared early in the design program. This plan should define corrosion prevention and control requirements consistent with the design life of the facility. The plan should describe the designer's approach to corrosion prevention of the HEMP shield and all electrical bonds associated with the HEMP barrier. Details should include:

a. Selection of compatible metals

b. Specific coatings to be applied

c. Passive or active protection systems to be employed

d. Ventilating, dehumidifying, and other methods to control the environment at the PEA and other potentially vulnerable areas of the HEMP shield

15.4 References.

15–1. "Military Handbook – Corrosion and Corrosion Prevention Metals," MIL-HDBK-729 (effective), Dept. of Defense, Washington, DC.

15-2. Fontana, M. G., Corrosion Engineering, 3rd cd., New York: McGraw-Hill, Inc., 1986.

15–3. Uhlig, H. H., Corrosion and Corrosion Control, 2nd cd., New York: John Wiley & sons, Inc., 1971.

15-4. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

15-5. "Corrosion Prevention and Protection," Army FM11-486-29, NAVELEX EE995-AA-GYD-010, Air Force TO 312-10-37, October 1983.

15-6. "Military Handbook - Electrical Engineering Cathodic Protection," MIL-HDBK-1004/10 (effective), Dept. of Defense, Washington, DC.

15-7. "Military Standard – Unified Code for Coatings and Finishes for DoD Materiel," MIL-STD-1516 (effective), Dept. of Defense, Washington, DC.

15-8. "Military Standard - Materials and Processes for Corrosion Prevention and Control in Aerospace Weapons Systems," MIL-STD-1568 (effective), Dept. of Defense, Washington, DC.

16. TESTING

16.1 Basic principles.

16.1.1 Test philosophy and types of tests. Because we do not operate systems in the HEMP environment, our experience in HEMP protection has been acquired solely from tests in simulated HEMP environments. It is also unlikely that we will acquire any indication of the adequacy of the HEMP protection of new systems from HEMP exposures during peacetime. Thus, our hardening design "experience," our determination of hardening adequacy, and our "feedback" on the effectiveness of the protection in operating systems are all generated from tests in which the HEMP effects are simulated in some way. This condition is unique to HEMP protection; almost all other aspects of system performance are exercised by normal operation of the system.

Because of this unique aspect of HEMP protection, testing and testability are important parts of the HEMP hardening effort. MIL-STD-188-125 (reference 16-1) requires an all-welded shield with a minimum number of points-of-entry, to make it possible to test each barrier element. Furthermore, the standard requires that all POEs be accessible for testing. Finally, the quality of the HEMP barrier is intended to be high enough that the residual HEMP stresses inside the barrier are too small to affect the internal equipment. Therefore, it is only necessary to test, monitor, and maintain the HEMP shield and the POE protective devices. The very complex interior of the facility should not be overstressed by the residual HEMP transients.

However, MIL-STD-188-125 recognizes that there are special cases in which it is impractical to install some mission-essential equipment (e.g. antennas) inside the HEMP shield. Therefore, MIL-STD-188-125 permits this equipment to be placed outside the HEMP shield, provided that appropriate special protective measures are used. It is also recognized that the residual stresses in some regions inside the HEMP barrier (e.g. high-power transmitters and transmitting antenna feed cables) cannot meet the allowable residual stress restrictions that apply to the protected volume. These regions are designated as special protective volumes.

16.1.1.1 Testing during construction. The complete HEMP test sequence for a facility that is hardened and demonstrated in accordance with MIL-STD-188-125 is illustrated in figure 143. During facility construction and equipment installation, two classes of tests-hardness assurance or quality assurance (QA) tests and acceptance tests-are performed.

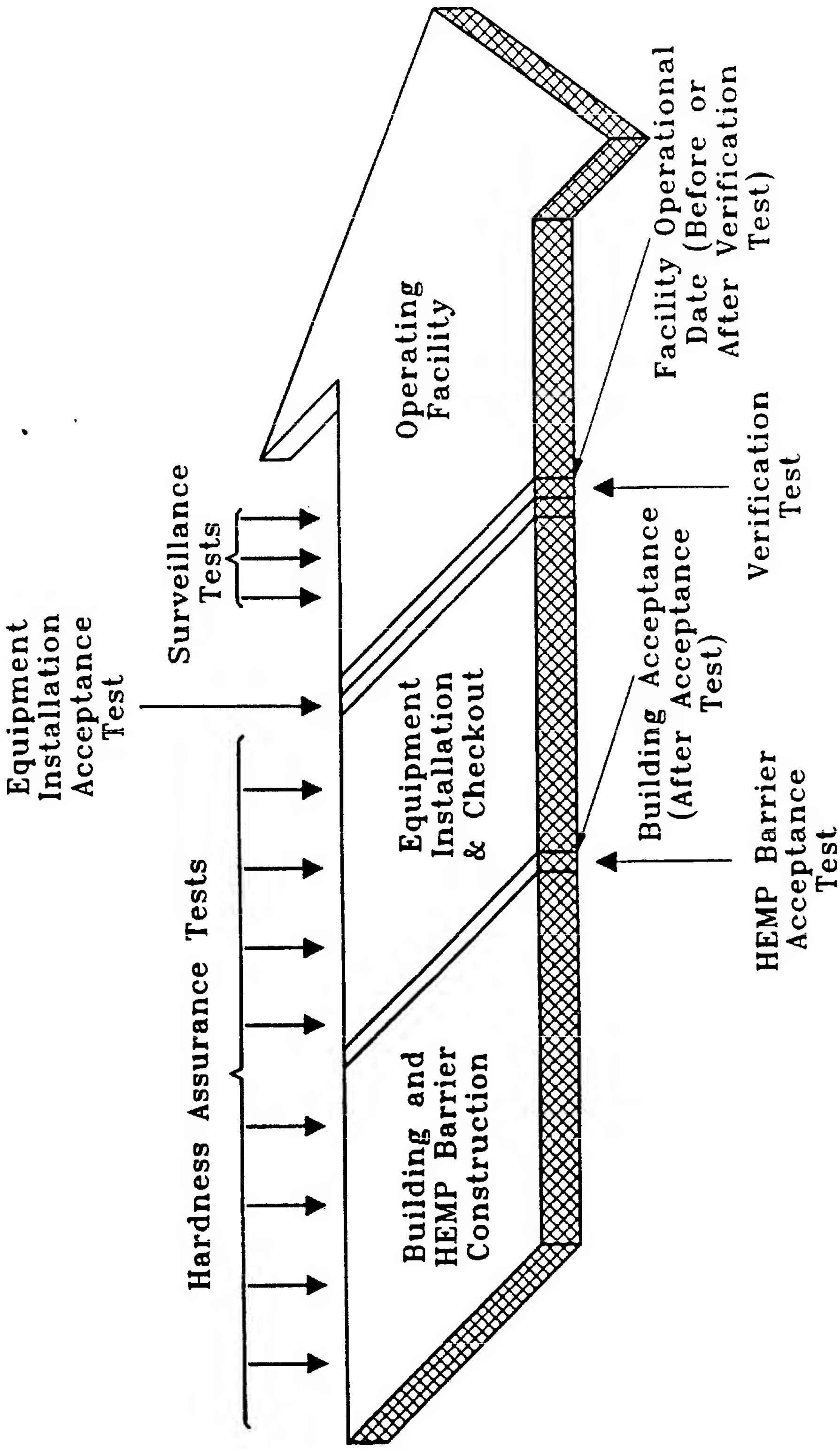


FIGURE 143. HEMP testing sequence.

The QA program is conducted to ensure that proper materials are used, that hardness critical components are properly fabricated, and that hardness critical installation processes are properly executed. Both factory tests and in-place tests are included. A major portion of the QA program is the in-progress weld inspections and tests, to ensure adequate quality and continuity of the welds used in the construction of the electromagnetic barrier. Many of these tests will be conducted whether or not the facility has a HEMP protection requirement. In general, the quality assurance tests are not threat relatable and do not use simulated HEMP. However, the tests do help to ensure that the completed facility will meet the HEMP protection requirements. The quality assurance tests required by the standard are described in subsection 16.3.1.

Results of the acceptance tests are the basis for accepting the HEMP barrier construction. The HEMP shield, the power filters and surge arresters, antenna cable penetrations, shielded doors, and ventilation POE protective devices are subjected to acceptance tests when this phase of the construction is completed and before the communications-electronics equipment is installed. The acceptance test establishes that the shield performance is acceptable and that the surge arresters, filters, and other barrier elements are properly installed and meet the requirements of the standard. Since the installation of the equipment is incomplete at this stage, the electrical POEs are provided with dummy loads for these tests. However, the currents injected for the tests are threat-like. Acceptance testing is also required for HCIs supplied in the C-E equipment installation phase. Because of the proximity to the facility hardness verification test, the installation acceptance and the verification sequences may be combined into a single experimental program. The acceptance tests are described in subsection 16.3.2.

16.1.1.2 Hardness verification tests. The hardness verification test is conducted on the completed facility, with the communications-electronics equipment installed and operating. The verification test includes a cw illumination test to determine the integrity of the shield and pulse current injection tests to evaluate the performance of surge protection and electrical bonds. For these tests, the performance of the C-E equipment must not be degraded and the residual stresses inside the barrier must not exceed the levels specified in the standard. Additional tests are also required for the special protective measures. The current pulses injected in these tests are threat-like, and the loads on the electrical POE are the operational system loads.

Any shortcomings in the HEMP protection detected during verification must be corrected before a satisfactory statement of hardness verification for the facility is prepared.

The verification tests are described in subsection 16.3.3. The timing of the HEMP verification test with respect to the construction, equipment installation, and operation of the facility is illustrated in figure 143.

16.2 MIL-STD-188-125 general test requirements.

4.4 HEMP testing. The HEMP testing program shall demonstrate that hardness performance requirements have been satisfied and that the required HEMP hardness has been achieved. This program shall include quality assurance testing during facility construction and equipment installation, acceptance testing for the electromagnetic barrier and special protective measures, and verification testing of the completed and operational facility.

4.4.1 Quality assurance program. A quality assurance program in accordance with FED-STD-368 and MIL-Q-9858 shall be implemented during facility construction and installation to demonstrate that the HEMP protection subsystem materials and components comply with performance requirements of this standard. The quality assurance test procedures and results shall be documented for use as baseline configuration and performance data for the hardness maintenance and surveillance program.

4.4.2 Acceptance testing. Acceptance of the HEMP protection subsystem shall be based upon successful demonstrations of compliance with hardness performance requirements of this standard. HEMP acceptance tests of the electromagnetic barrier and special protective measures shall be conducted after all related construction work has been completed. Acceptance test procedures and results shall be documented for use as baseline configuration and performance data.

4.4.3 Verification testing. After completion of the HEMP protection subsystem and installation and operational checks of the facility equipment, HEMP hardness of the facility shall be verified through a program of tests and supporting analysis. The verification program shall prow-de a definitive statement on the HEMP hardness of critica/, time-urgent mission junctions at the facility under test. Verification test procedures and results shall be documented for use as baseline configuration and performance data.

16.3 Applications.

16.3.1 Quality assurance testing.

16.3.1.1 MIL-STD-188-125 quality assurance test requirements.

5.1.3.4 Shield construction quality assurance.

5.1.3.4.1 In-progress inspection of welded and brazed seams. In-progress inspection of welded and brazed seams and joints shall proceed continuously in parallel with the shield fabrication and assembly activity. The quality of all shield seams and joints, including those used for installation of POE protective devices, shall be monitored with visual and magnetic particle inspection, SELDS measurements, or dye penetrant testing.

5.1.3.4.2 Shielding effectiveness survey. After the shield is closed but before interior equipments and finishes are installed, a shielding effectiveness survey shall be performed. SELDS testing and plane wave shielding effectiveness tests shall be employed. Shield defects found during the survey must be corrected, retested, and shown to prom-de the required performance before the interior equipment and finishes are installed.

5.1.4.1.1 Quality assurance for architectural POE protective devices. All welded or brazed seams and joints required for installation of architectural POE protective devices shall be monitored under the program of in-progress inspection of welded and brazed seams (see 5.1.3.4.1). Shielded doors and other closure or access covers shall be subjected to electromagnetic and mechanical quality assurance tests to demonstrate acceptable performance.

5.1.5.1.1 Quality assurance for mechanical POE protective devices. All welded and brazed seams and joints required for installation of mechanical POE protective devices, including those for piping and ventilation penetrations, shall be monitored under the program of in-progress inspection of welded and brazed seams and joints (see 5.1.3.4.1).

5.1.6.2 Quality assurance for structural POE protective treatments. All welded and brazed seams and joints required for structural POE treatments shall be monitored under the program of in-progress inspection of welded and brazed seams (see 5.1.3.4.1).

5.1.7.2 <u>Quality assurance for electrical POE protective devices</u>. All welded and brazed seams and joints required for installation of electrical POE protective devices shall be monitored under the program of in-progress inspection of welded and brazed seams (see 5.1.3.4.1). Transient suppression/attenuation devices shall be subjected to electrical and mechanical quality assurance tests to demonstrate acceptable performance.

5.1.8.4 <u>Quality assurance for special protective measures.</u> Quality assurance tests shall be conducted to ensure that special protective measures comply with performance requirements for the particular installation.

16.3.1.2 Quality assurance program. A HEMP hardness assurance program is implemented during the facility construction and equipment installation phases to ensure that the HEMP protection subsystem is being implemented in accordance with the project drawings and specifications. The Government, as well as the construction and installation contractors, has a role in quality assurance. The role, responsibilities, and relationships of each are covered in the following paragraphs. Emphasis is on the activities, inspections, and tests to be performed.

It is helpful to distinguish between the Government's role and that of the contractor. The term "quality assurance," while referring to the overall program, is also sometimes used to denote the Government's (construction agency's) role and responsibilities for ensuring that an acceptable product is provided to the user. The term "quality control" (QC) can designate the role and responsibilities of the contractor. While this usage is not universal, it will be followed here.

The HEMP quality assurance/quality control program is an integral part of both the design and construction phases for a hardened facility. Both contractors require HEMP expertise and qualifying experience. The architect-engineer should develop a QC plan and establish an organization for ensuring the quality of the drawings and complete definition of the test requirements in the specifications. The construction contractor's QC plan and organization must ensure that all tests are performed properly and that the results are correctly interpreted. Similarly, the Government reviewers during design and the inspectors during construction must have the needed HEMP QA expertise to adequately monitor the contractors' activities.

16.3.1.3 Quality assurance principles. Quality assurance is the organized process of inspections and tests that are accomplished to ensure that a product, facility, or system is constructed or fabricated in accordance with the associated drawings and specifications. For purposes of this handbook, this definition is narrowed to encompass only the elements

of the HEMP protection system. Often there is some overlapping of the normal project QA and HEMP QA. An example would occur in the case where the HEMP shield is an integral part of the structure.

For HEMP QA to be effective, planning must start during the initial programming phase. Manpower and resources required for Government supervision must be made available. Specification of the construction phase HEMP QC is accomplished in the project HEMP specifications. Implementation takes place during procurement, fabrication, construction, and installation. Quality assurance and quality control are integral parts of the acceptance process.

Government QA on a construction project normally takes the form of a site inspector. The amount of time spent at the project location depends on the size of the project and the number of projects being implemented by the construction or installation agencies. HEMP QA has specialized requirements, which are not normally a part of the Government inspector's training. Hence, HEMP expertise is made available on site during all significant HEMP construction/installation activities, often through contract action. The HEMP QA inspector witnesses inspections, tests, and other activities performed by the contractor QC personnel. This person also performs independent HEMP inspections and tests on behalf of the Government to check the quality of the HEMP protection subsystem and to verify the adequacy and performance of the contractor's QC process. This HEMP expert can also aid in the resolution of HEMP-related construction problems.

QC is an integral part of all construction projects. HEMP QC is a separable part of project QC that can only be successfully accomplished by a person trained and experienced in HEMP QC. Therefore, the requirements and responsibilities for the contractor's quality control personnel must be clearly defined in the project HEMP specifications.

QC activities include reviewing submittals, inspecting incoming HEMP subsystem materials and components, qualifying HEMP welders and welding procedures, inspecting the construction/installation of the HEMP protection subsystem, performing in-progress weld inspections and tests, monitoring all HEMP-related construction problems, and reviewing all HEMP-related requests for waivers and changes. The HEMP QC inspector has an overall responsibility for the quality of the as-built and as-installed HEMP protection subsystem.

It is not the responsibility of the HEMP QA program to ensure that the site construction is in accordance with MIL-STD-188-125 or any other document that is not part of the construction contract. For a site to be constructed and tested in accordance with

MIL-STD-188-125, the contract drawings and specifications must comply with that standard. If, however, the QA or QC representative determines that the project does not meet certain aspects of the standard, there is a responsibility to inform the proper project authorities of this problem.

HEMP QA/QC, as described in this subsection, covers all significant, related activities until the time of acceptance testing. On many projects, acceptance testing is the final event of the QA/QC program in the construction and the equipment installation phases, unless a deficiency list containing HEMP protection subsystem entries remains.

16.3.1.4 Quality assurance documents.

16.3.1.4.1 Project QC specifications. The construction contractor will establish a HEMP QC program and implement effective quality control procedures only if these are explicitly required by the project HEMP specifications. The HEMP specifications are normally found under Division 13, Special Construction. The protection subsystem performance requirements in the specifications, in combination with the design drawings, must completely define the HEMP-hardened facility. Additionally, the specifications must prescribe the hardness assurance requirements in complete detail. It is this QC program that ensures the HEMP protection subsystem is correctly implemented in accordance with the project drawings and specifications.

Proper QA/QC depends on clear delineation in the project HEMP specifications: approval of submittals only after proper HEMP consideration; descriptions of components and materials; installation, welding, acceptance, and testing specifications. QA/QC is an integral part of virtually all projects. HEMP QC must be made an integral part of all HEMP construction/installation projects. It is not sufficient to merely have HEMP QC; it must be properly defined. There now exists sufficient project experience upon which to formulate a successful HEMP QC program. Certain elements must exist. Certain activities must take place.

If HEMP inspections and tests are to be conducted on a HEMP construction project, they must be specified. This is normally accomplished by including the requirements in the project HEMP specifications. The requirements may be included as part of the normal QC requirements or they may be addressed separately. It is very important to clearly define what is required. If requirements for a test plan, test, and test report do not appear explicitly, submittals will not be provided and the testing will not be conducted.

Provisions of the sample guide specifications in appendix A illustrate the various points which must be included in the project HEMP specifications to ensure that HEMP QC is adequately addressed.

16.3.1.4.2 HEMP QC plan. Requirements for the QC plan, defined in the project HEMP specifications, indicate for the bidder the type and level of response that must be provided, in the contractor's bid and in the contractor's staffing of the contract. These requirements also define for the Government's project QA personnel what the contractor must provide.

This plan, and the included procedures and reports, become the major instrument for implementing HEMP QC on the project. Qualified HEMP personnel must be involved in the approval process for the plan, since it has such a major impact on the eventual HEMP integrity of the facility.

16.3.1.4.3 Submittal review. HEMP expertise must be available during the review of all HEMP-related submittals. Many well-designed HEMP projects have inadvertently been "poorly" redesigned during the submittal phase. Contractors have used products that were not appropriate for the particular application. Major changes had to be made in the design of the shield to accommodate these components. The results were often unsatisfactory. One major mistake at this point in a project can more than offset the cost of having adequate, experienced HEMP QA/QC. It is important for both the Government and the contractor to have adequate HEMP expertise and experience. HEMP-qualified personnel on both sides are needed to construct a cost-effective HEMP-hardened facility.

On successful HEMP construction projects, the submittal review procedure has been modified to incorporate the specialized requirements that are a part of HEMP-hardened facility construction. The HEMP-related submittals are reviewed by personnel with HEMP expertise. If the reviewing organization has HEMP expertise available to them, it should be used in the submittal review and sign-off process. Otherwise, HEMP expertise can be obtained from another Government agency or by contract. In the final analysis, successful projects have had local QA/QC personnel, experienced in HEMP construction, who have been an integral part of the submittal review process. Local project personnel are familiar with the project requirements, design, and local site conditions. Often they are in a better position to evaluate many of the submittals.

16.3.1.5 Storage inspections. HEMP construction inspections are many and varied. One of the earliest inspections is an examination of the storage area for HEMP materials and components. Numerous projects have run into serious and costly problems that have resulted from improper handling and storage of materials and components. One example

concerns a site where materials were improperly stored over a winter. In the spring, when it was time to use these materials, they were found to be corroded, damaged, and in some cases heavily caked with mud.

A common problem at construction sites involves the storage and handling of the steel sheets to be used in the construction of the HEMP shield. Sheets often are stored on the ground or on a coarse frame. Fork lifts are used to transport the sheets to the location where they are to be installed. The result is sheets which are damaged, rusted, and caked with dirt. QC must ensure that components and materials are properly stored and handled. The HEMP specification must also properly define storage and handling requirements.

16.3.1.6 Receiving inspections. Inspection of incoming shipments is an important activity for the QC inspector. Each component and material must be carefully inspected for damage that may have resulted from shipment. Each item must also be inspected for full compliance with its specification. If an item is required to be certified, its certification must be verified. If the item was factory accepted or type tested, the results must be provided. Defective items and inadequately documented items must be rejected.

16.3.1.7 Welding inspections and tests. Welders and welding processes are to be qualified in accordance with the requirements in the HEMP specifications. Welding materials and gases are to be checked against specification requirements. Regardless of the experience of a welder, the performance on the current job must be monitored. The QC inspector must ensure that each welder provides a positive indication, mark, or symbol, on all welds made by him or her. If an unacceptable number of defects are found, a determination must be made whether the defective welds are made by one individual or are being made by all (or most) of the welders. If the defects are attributable to only one welder, that individual is normally subject to requalification or dismissal from the job site. If several welders are causing similar defects, the procedures should be reexamined.

Daily inspections are made as the construction of the HEMP protection subsystem progresses. Erection in accordance with the approved shop drawings must be verified. All welded or brazed seams and joints are visually inspected. Questionable, obviously defective, or missing welds are to be clearly marked by the QC inspector, and they must be brought to the attention of the welders or their supervisor.

Welding of the shield is generally accomplished on only one surface of the shield. If the welder should weld part of an area or plate on one surface and the remaining segment on the other side, a void will likely occur at the location of the transition—unless special

precautions are taken. These defects are often difficult and costly to find and repair, especially if the defect is not discovered until the final acceptance test.

Inspections and tests of the floor shield are made prior to pouring the wear slab, if the facility is so designed. Floor penetrations are verified to be in accordance with the drawings. Repairs required after the concrete pour are costly and difficult to make.

Inspections of the locations and methods of construction of all openings and penetrations are made. Cross-sectional and length dimensions of waveguides are checked. All shield surfaces are checked for compliance with the penetration schedule.

Magnetic particle, dye penetrant, or shielded enclosure leak detection system (SELDS) inspections are conducted where specified or required. It must be recognized that successful completion of visual inspections and magnetic particle, dye penetrant, or SELDS tests does not relieve the contractor from verifying performance in accordance with the acceptance test requirements.

QC inspections continue throughout the construction phase. During the shield erection and assembly phase, the inspections are primarily designed to ensure that the shield is being properly installed. Once the shield is in place, the emphasis of the inspections is on the installation of the penetration treatments. After this phase is complete, emphasis is on ensuring that the installation of the interior and exterior finishes does not in any way degrade the shield. Various finishing tradespersons often will attempt to make unauthorized (compromising) penetrations in the shield or changes to the shield penetration devices. Regular inspections should guarantee that there are no changes to the electromagnetic barrier between the time of the prefinal test and the final acceptance test.

Salient features of the visual, magnetic particle, and dye penetrant inspection methods are covered in the following paragraphs. SELDS testing is addressed in 16.3.1.8.

16.3.1.7.1 Visual inspections. All welded and brazed seams and joints are to be visually inspected. MIG or TIG welds can be inspected without the need to remove slag. Lighting should be sufficient for easy viewing. A magnifying glass will aid in locating defects. The visual appearance of a sound weld is normally noticeably different from the appearance of an unsatisfactory weld. A satisfactory HEMP weld is characterized by adequate fusion, no noticeable porosity, no undercuts, no cracks, no weld spatter, little or no overlaps, and it has a generally consistent appearance.

A trained HEMP QC inspector can detect a large percentage of faulty welds. There is no foolproof, cookbook method for showing others how to spot bad welds. Nothing

takes the place of experience. However, figure 144 shows some examples of weld beads, both good and bad. The most obvious characteristic of a satisfactory joint is good fusion; the weld material melts into the surrounding metal with no porosity (holes or gaps in the weld). Most MIG and TIG welds are made using a skip process. A small segment is welded. The welder then moves to another location, away from the heat created by the previous weld. After the first welded segment has cooled, a second strip or segment is then welded. This skip weld process is utilized to keep the base metal from being excessively heated, causing the steel to warp or "oil-can."

Visual inspections are the first step in assessing the quality of HEMP welds during the construction of the HEMP shielding system. Each welder performs a self-inspection, which is then followed by the QC inspector's examination. The general quality of the HEMP welds is monitored on a real-time basis. Welding current and voltage settings are normally optimized as a result of these visual inspections. However, visual inspections are not intended to replace in-progress weld tests.

Weld inspections are expected to at least identify obvious faults. Figure 145 shows some of the obvious defects found in HEMP welds. A weld with poor fusion can be easily recognized by an experienced inspector. Its major characteristic is that the molten metal of the weld does not sufficiently heat the adjacent weldments. A cracked weld is easily identified. If the weld is porous, there will be visible voids or pin holes. If a weld has a poor appearance, there may be a valid reason for questioning the equipment, its settings, the gas mixture, the welding wire or rods, the gun, cleanliness of the surface, or the skill of the operator.

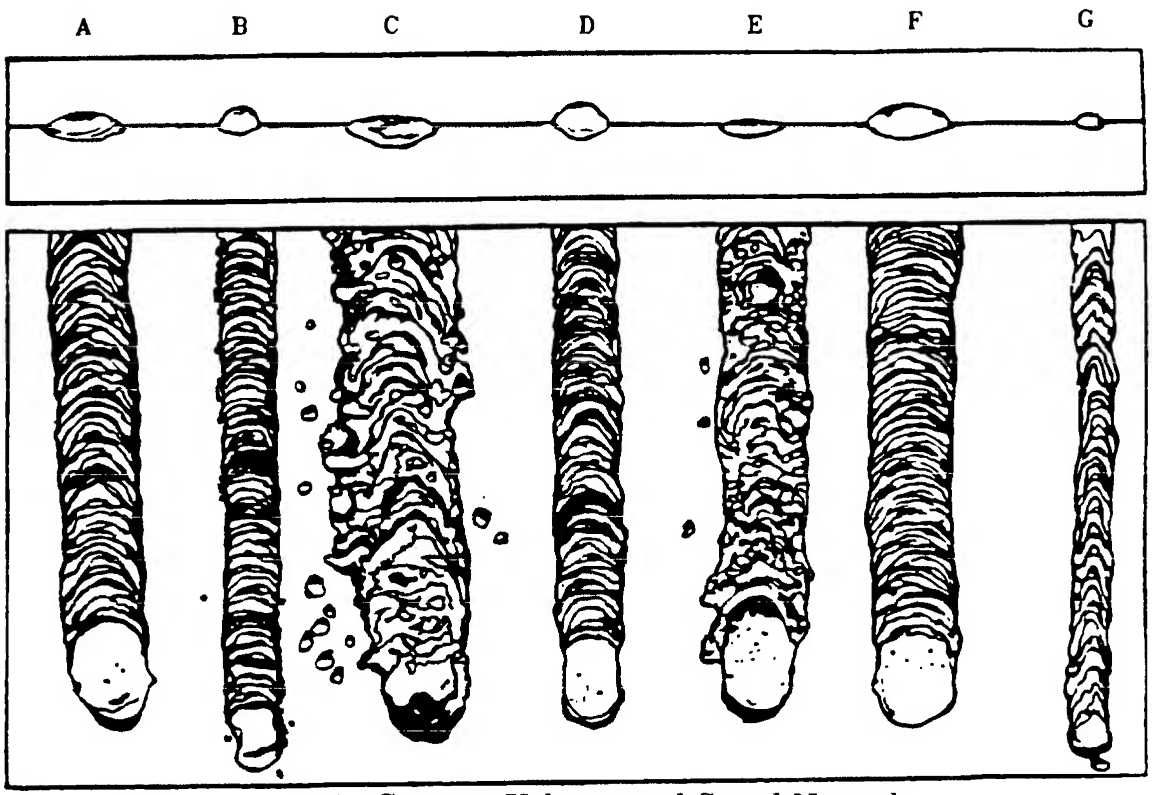
16.3.1.7.2 Magnetic particle testing. There are many slightly different magnetic particle test techniques. However, all methods consist of the same sequence of three basic operations:

a. Establish a suitable magnetic field in the test object.

b. Apply magnetic particles to the surface of the test object.

c. Examine the test object surface for accumulations of the particles (indications); evaluate the quality of the welded joint.

One advantage of magnetic particle inspection is that it can detect all surface and most subsurface discontinuities in thin sheets of a ferromagnetic metal. By examining the indications, an inspector can determine their cause. Not all indications are the result of weld defects; sharp edges, corners, and irregular geometries also cause indications because they cause changes in the magnetic field distribution. Each discontinuity in effect sets UP



A. Current, Voltage, and Speed Normal
B. Current Too Low
c. Current Too High
D. Voltage Too Low
E. Voltage Too High
F. Speed Too Slow
G. Speed Too Fast

FIGURE 144. Examples of weld beads.

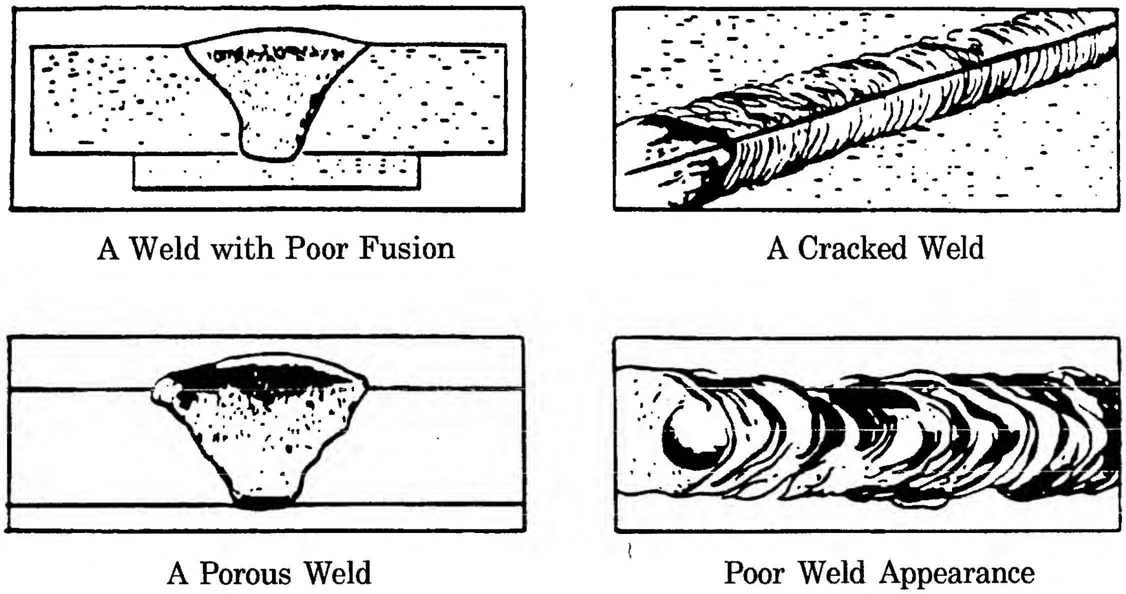


FIGURE 145. Examples of unsatisfactory or poor welds.

a small magnetic dipole; the magnetic particles collect and form a pattern around these poles. Surface defects produce patterns that are sharp because the particles are tightly held by the leakage flux. In contrast, subsurface defects produce a rather fuzzy pattern.

There are many variations on the three basic operations mentioned above. The magnetic field can be established three ways: by passing an electric current through the object, by passing an electric current through a conductor surrounding the object, or by an electromagnet or permanent magnet. An electromagnet, known as a yoke, is the most practical for HEMP shield testing and is illustrated in figure 146.

Current for the electromagnet can be ac, dc, half-wave rectified ac, or full-wave rectified ac. Half-wave rectified ac current is the most effective for the detection of surface and subsurface defects. It imparts a very noticeable pulse to the particles, giving them mobility and aiding in the formation of indications.

Actual magnetizing current level should be established experimentally. Factors such as metal thickness, presence of backing strips, geometry, and size of the yoke all have an effect on current requirement. If the current is too low, the field generated is not strong

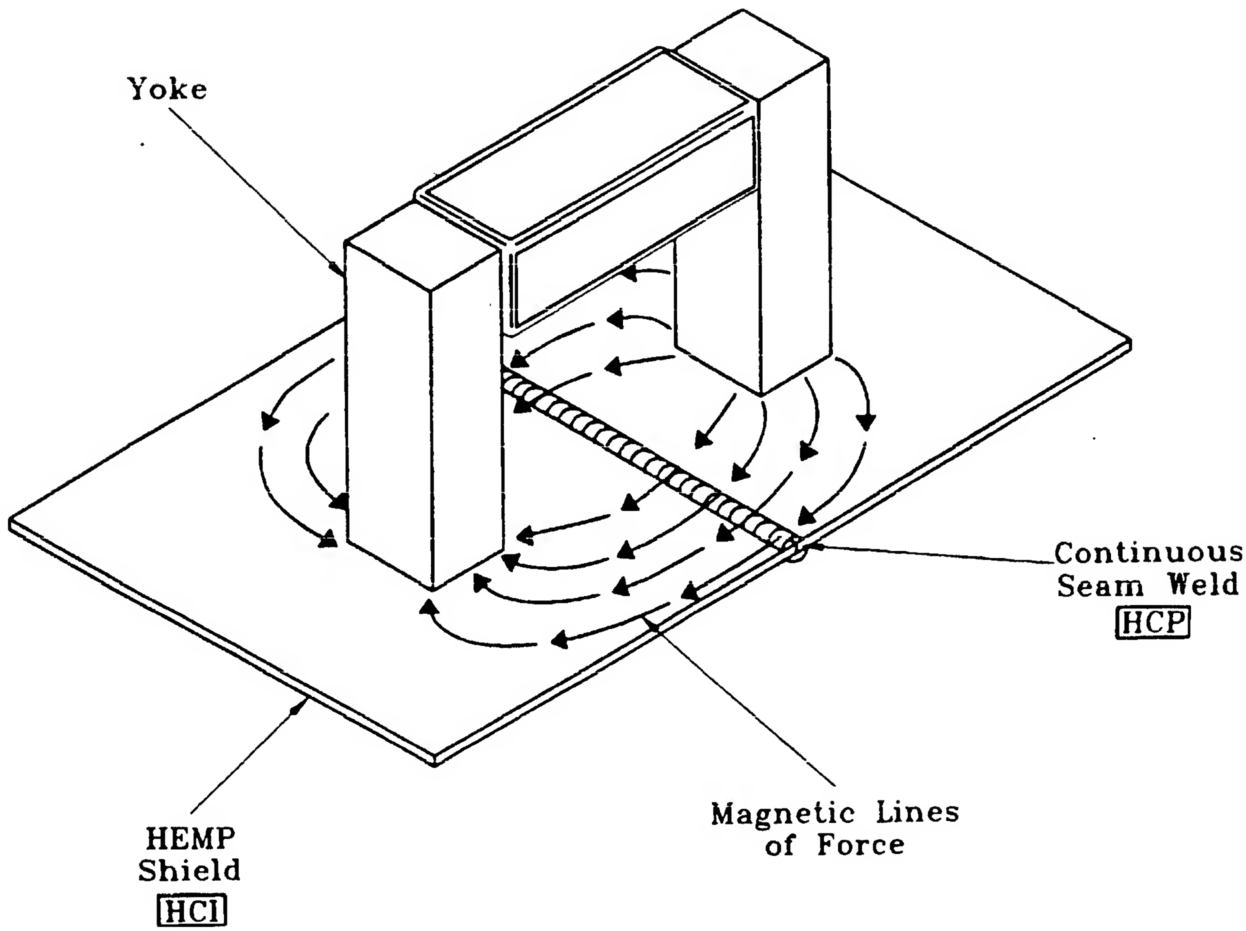


FIGURE 146. Magnetic particle testing.

enough to form particle patterns. If the current is too high, patterns may form where no discontinuities are present and will be difficult to interpret.

In general, defects are detectable if the magnetic field lines are perpendicular to the axis of the defect. For this reason, a thorough magnetic particle inspection of welded sheet metal requires two yoke orientations, one at right angles to the other. Most defects, such as lack of weld fusion, will be parallel to the weld line and, hence, detectable by placing the yoke across the weld. This single yoke orientation is probably sufficient for most situations. The exception might be the floor shield where shielding effectiveness tests often cannot be done.

There are also variations on how the particles can be applied. Particles can be dry or in a liquid suspension. Either is acceptable, but dry is preferred because they have less tendency to be held by surface roughness. Wet particle application may have an advantage

in overhead work. Particles can also be applied during or after the magnetizing operation. The first technique is known as 'continuous," and the latter is known as 'residual." The continuous technique is preferred because it is more sensitive. Dry particles are best applied above the test area. This gives the particles an opportunity to line up with leakage flux as they approach the weld. Excess powder is removed with low-velocit y air. Remaining particles are indications of discontinuities and possible defects. In general, particles should be very fine and have high permeability and low retentivity. Color is chosen to provide maximum contrast.

Magnetic particle inspection can be done from one side of the shield and, if properly conducted, can be an excellent test of both the mechanical and electromagnetic soundness of shield welds.

16.3.1.7.3 Dye penetrant inspection. Dye penetrant inspection is also used to supplement in-progress visual inspections for both welded and brazed joints. This form of inspection is most commonly used as a means for evaluating HEMP welds on partially completed shield surfaces, particularly when the geometry makes magnetic testing impractical.

There are two common dye penetrant methods: one-side (one surface of a shield) and two-side inspection. For most HEMP construction applications, the one-side method is most commonly used. Both sides of the shielding surface must be available for inspection if the two-side inspection method is to be used.

In the dye penetrant inspection method, surface defects are found by the use of liquid dyes which have high fluidity. These liquids have good nettability and are readily drawn into all surface defects by capillary action. Application of a suitable developer brings out the dye and outlines the defect.

While specifications covering the dye penetrant inspection method exist, the common practice is to use a commercially available dye penetrant kit. All necessary materials and instructions for their use are furnished with such a kit. The dye and the developer normally are contained in small pressurized cans. The essentials of the method are:

a. Application of the penetrant

b. Penetration of the defect by the dye penetrant

c. Removal of the excess penetrant from the surface

d. Development of the indication

e. Inspection

The surface to be inspected, which must be clean and dry, is coated with a thin film of the penetrant. After allowing time for the penetrant to flow into the defects, usually 10 to 20 minutes, the area is wiped clean. Only the penetrant in the defects remains. An absorbent material, called a developer, is applied to the weldment and allowed to remain until the liquid from the imperfection is drawn into the developer. The dye now clearly outlines the defects.

Typical defects found by this method are surface cracks and shrinkage, porosity, and through leaks. Examples include shrinkage cracks and shrinkage porosity, fatigue cracks. and heat cracks, seams, lack of bond between two joined metals, and through leaks in welds. Only those defects which are open to the surface will be detected since penetration of an open defect is required for a defect indication.

Some of the penetrants used contain a fluorescent dye. The method of applying and developing is the same as for the previously mentioned dye penetrants. However, the fluorescent penetrant must be viewed under ultraviolet light. This light causes the penetrants to fluoresce to a yellow-green color, which is more clearly visible than the nonfluorescent dye penetrants.

Dye penetrant inspection, while it is an important tool in the weld inspection process, also has its limitations. Experience has shown that the dye penetrant method has provided a positive indication of some defects which have not been found to be electromagnetic defects. Conversely, electromagnetic defects have been found in HEMP shielding surfaces that have passed the dye penetrant inspection.

16.3.1.7.4 Other weld test methods. Other weld inspection methods include eddy-current testing, radiography, and ultrasonic inspection. Each of these methods is suitable for shop testing of shop-fabricated weldments, but impractical for use in monitoring the barrier assembly field welding.

In eddy-current testing, the part to be examined is placed within or adjacent to an electric coil in which an alternating current is flowing. This exciting current causes eddy currents to flow in the part as the result of electromagnetic induction. The eddy current distribution depends upon the electrical characteristics of the part. Flaws or cracks impede the eddy current flow and can be observed either by monitoring the feedback to the exciting coil or the induced response in a secondary coil. Eddy-current testing can be performed on either ferromagnetic or nonferromagnetic weldments.

Radiographic inspection is a method for determining the soundness of a weldment by means of radiation capable of penetrating through the entire weldment. X-rays and gamma rays are used to penetrate the metal. A permanent record of the internal structure is obtained by placing sensitive film in direct contact with the back of the weldment. When these rays pass through a weldment of uniform thickness and structure, they impinge upon the sensitized film and produce a negative of uniform density. If the weldment contains any imperfections, more rays will pass through the less dense areas (defects) and will register on the film as dark areas, clearly outlining the defects. It is doubtful that this method has ever been used in monitoring HEMP shield assembly, because it requires unrestricted access to both sides of the shield and because of high cost.

Ultrasonic inspection uses high-frequency sound waves to locate and measure defects in both ferrous and nonferrous materials. This method is very sensitive and is capable of locating very fine surface and subsurface cracks, as well as other internal defects. Ultrasonic testing is most effective on weldments thicker than 0.5 cm (0.2 in). If a high-frequency sound wave is sent through a defect-free piece of metal, the signal will travel through the metal and be reflected from the other side. Results are shown on a calibrated screen of an oscilloscope. Discontinuities interrupt the signal and reflect it back sooner than the signal in a defect-free material, This interruption is shown as a line on the oscilloscope screen and indicates the depth of the defect. Only one side of the weldment needs to be exposed for testing purposes. Again, other methods are much more efficient to use at a construction site and will provide adequate weld quality information.

16.3.1.8 SELDS tests. In-progress SELDS tests of primary shield welds should be conducted throughout the construction of the HEMP shield. These tests are started as early as possible during the construction of the shield, to obtain electromagnetic information on the integrity and quality of the welds. The SELDS method can be used at almost any stage of construction, but it is most accurate and efficient when used after the facility electromagnetic barrier is fully complete.

While the SELDS test is used as an in-progress test during construction, it is also used in preparation for the acceptance test. The final SELDS test during construction is accomplished when the barrier is complete, prior to the final acceptance test. Furthermore, the SELDS technique is frequently the basis of the built-in shield monitoring capability required by MIL-STD-188-125. Such a permanently installed setup is used for life-cycle hardness surveillance testing. The following paragraphs describe the SELDS test method, how it is normally prescribed, and how it is used on a project. A permanent test installation is also discussed.

16.3.1.8.1 SELDS test method. The SELDS test is an electromagnetic method for locating leaks in a high-quality shield. It can be employed to evaluate all types of welded and brazed joints, including seams, patches, and the welds for installation of the POE protective devices. During construction, the welds used to fabricate and assemble the HEMP electromagnetic barrier are 100 percent tested by the SELDS technique. All defects found by this method are marked and repaired before performing the shielding effectiveness acceptance test (see 16.3.2.3).

SELDS equipment is available commercially from several manufacturers. It consists of two units—a transmitter or generator and a small, hand-held detector/receiver. The operating frequency is generally about 100 kHz. The transmitter must typically be connected to ac power, while the receiver operates from batteries.

The SELDS is principally designed to locate defects in a continuous, closed shield. The excitation of the shield is an rf current supplied by the transmitter, which is directly connected to opposite corners of the area to be tested. Figure 147 illustrates SELDS leads from a test cabinet, where the transmitter is connected, to a variety of shield drive points. The current excitation is usually applied to the outer surface, so that the detector operates in the low-noise environment inside the barrier. If the rf current encounters an electrical discontinuity, such as a faulty weld, the magnetic field will leak through the defect. The strongest component of the leakage field will be normal to the shield surface.

The detector/receiver is used to survey the surface on the side of the shield opposite to that which is excited. A small loop in the detector senses the normal magnetic field and produces an output proportional to the leakage field amplitude. The detected signal strength is indicated by the reading on the receiver meter and by the sound level of an audible tone provided to a speaker or earphones.

The size of the area which can be tested in a single excitation configuration is a function of the particular equipment, since different models have different transmitter output power and detector sensitivity. Several past projects have specified 400 m^2 (4300 ft^2) as the maximum area to be excited and tested using a given pair of test leads. Additional, intermediate drive points must be provided, as necessary, on larger surfaces.

Loop antennas, rather than direct drive connections, are sometimes used to excite the shield surface. The SELDS loop excitation method is illustrated in figure 148.

When SELDS is used to evaluate weld integrity during early stages of construction when the shield is not closed, the tester must exercise special care in interpreting the measurements. If the SELDS technique is used to check the floor shield before the walls

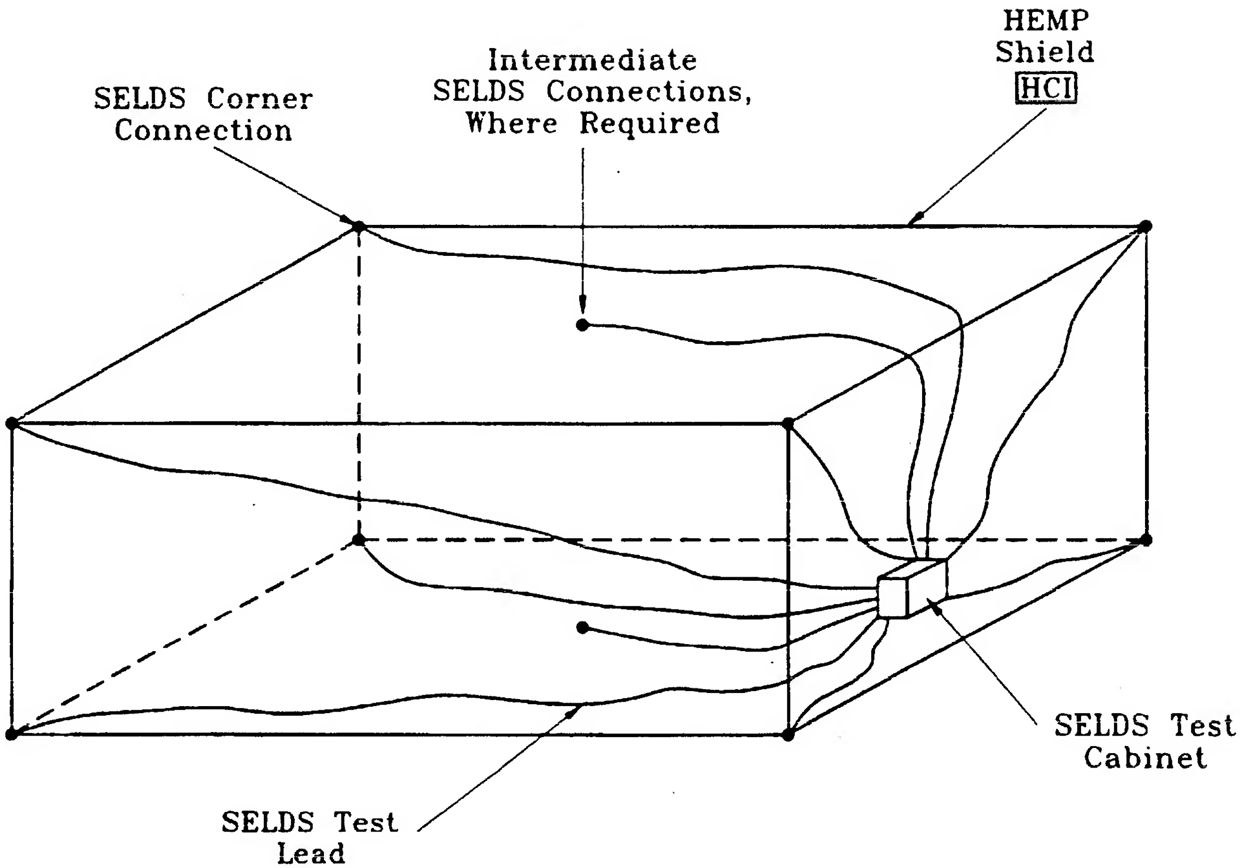


FIGURE 147. Typical shield drive SELDS test setup.

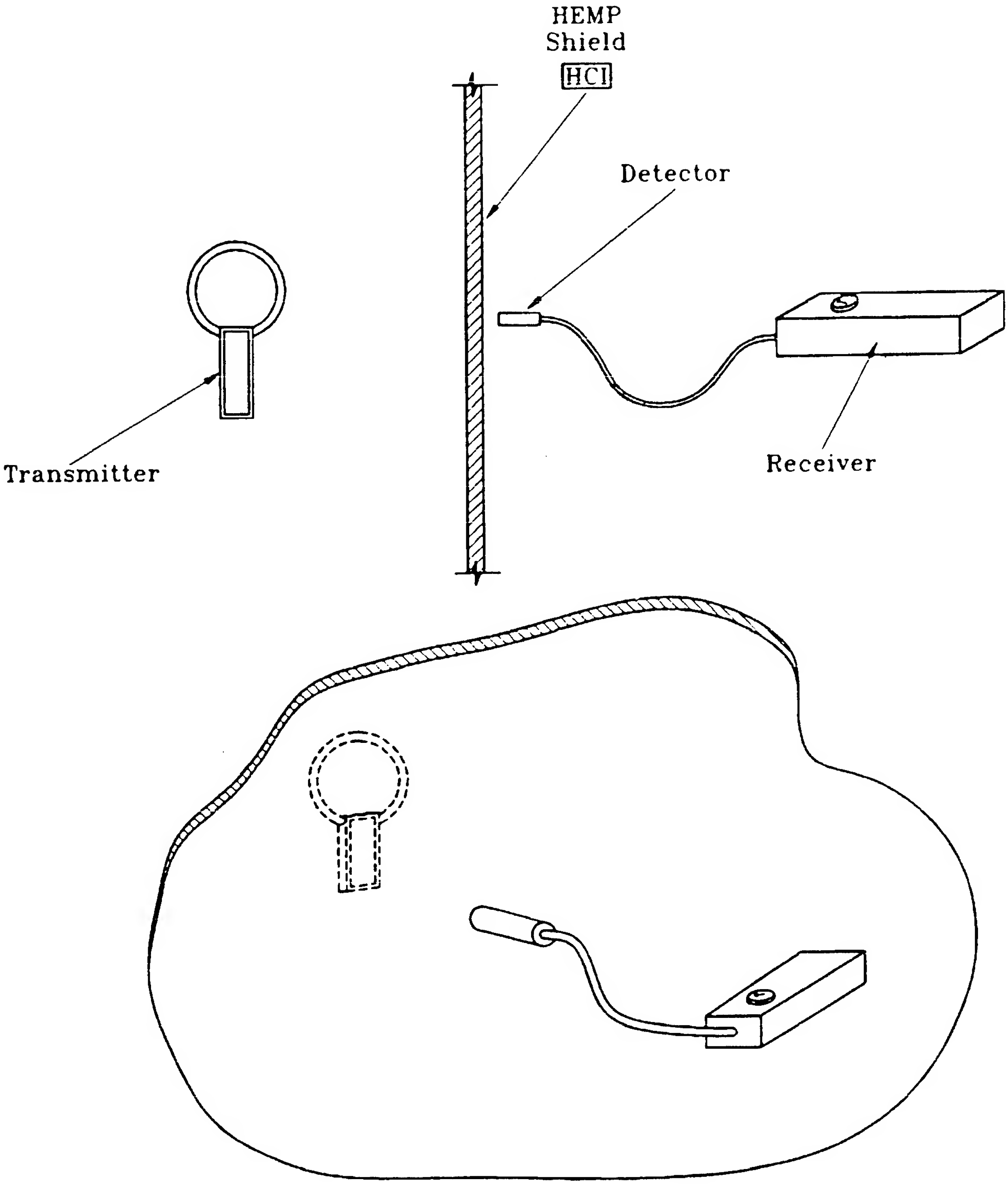


FIGURE 148. SELDS testing with loop excitation.

are erected, for example, the SELDS test leads are connected to opposite corners of the floor. In this configuration, reasonably accurate results can be obtained over most of the surface. Readings near the edges of the floor will be invalid, however, due to signal pickup from the exciter test leads. There will also be significant background noise, both from the exciter leads and from the surrounding electromagnetic environment, since the enclosure is not complete.

16.3.1.8.2 Permanently installed SELDS. MIL-STD-188-125 requires a built-in monitoring system that will detect significant changes in the electromagnetic barrier performance. One such system employing permanently installed SELDS drive points is described here; other approaches are discussed in section 17.

On a given project, SELDS equipment may be furnished by the construction contractor or it may be furnished by the Government. In some projects, only the test leads and test cabinet are installed as part of the construction project.

SELDS test leads/connections are provided on all shield surfaces, in accordance with the construction drawings, to support the preliminary shielding effectiveness test and hardness surveillance tests. This same setup also may be used to conduct the in-progress tests. The construction drawings should show the actual locations for connecting the various test leads. Normally, the test leads are attached to the outside surface of the shield. This will allow the detector to be used on the inside surface of the shield.

The SELDS test cabinet serves as the connection point for the output of the SELDS transmitter, which is connected only when a test is in progress. SELDS test cabinets are provided as shown on the drawings. For a normal test setup, the cabinet is located in a weather-protected area outside the barrier. The number of cabinets required is a function of the size and layout of the building. Each cabinet should be constructed of 2-mm (14-gauge) steel, with a hinged cover or door. An appropriate number of insulated screw type terminal strips, for the test leads, are provided. Terminals and test leads are identified with a suitable nameplate of laminated plastic, engraved with test point numbers. A separate laminated plastic test lead location diagram (with test lead routing and connection point numbers shown) should be placed on the inside of the cabinet cover.

Test leads should be insulated and should be no longer than 45 m (150 ft) in length. Stranded copper conductors, 2-2.5 mm in diameter and bonded to the shield only at the end, are recommended because solid wire can be more easily broken. The surface area of the shield will determine the number of test leads (drive points) that are required. The distance between test lead connections on a shield surface should not be more than 20 m (66 ft). If more than one test cabinet is required for a given area or building, test leads

that would be common to different surface areas should be duplicated at each test cabinet to ensure that test point pairings are maintained.

Bonding of the test leads to the shield is accomplished by brazing or high-temperature soldering. Test leads should be protected throughout their length, from the bonding point to the test cabinet, with plastic pipe. The contractor must ensure that lead installation is properly sequenced since, in most cases, attachment of the leads following construction will be very difficult or impossible. Several test leads may be run in the same conduit, as long as the leads are fully insulated from each other. Extreme care must be exercised in the placement of the wires, to ensure that the leads are not damaged, shorted, or opened during welding of the HEMP protection subsystem.

It should be noted that the system described here will produce a nonuniform surface current density on the outside of the shield. The surface current density will be largest near the test lead connection points and under drive wires. Thus, small changes in the barrier performance can be inferred only from meter reading differences from a baseline set of internal measurements.

16.3.1.8.3 Limitations and attributes of SELDS method. The SELDS method is a very effective technique for locating anomalies and defects in a HEMP protection subsystem. However, the method is neither perfect nor a substitute for shielding effectiveness acceptance tests required by MIL-STD-188-125.

The optimum condition and time for using this technique is at a time when the shield is complete and no finishing materials are in place. Using the SELDS method at earlier times in the construction, while very helpful and often necessary, is not without risks. Background noise masks the results. Particularly at early stages of construction, the effectiveness of the SELDS test depends on the skill of the tester. The earlier the tests are performed, the more experience and ingenuity is required from the tester.

A defect may be missed by the tester if the weld defect is not sufficiently excited because of the location of the test leads. Conversely, some defects found during SELDS testing and not subsequently repaired may not be points of failure during later rf shield attenuation tests. However, SELDS tests at an early stage can find significant problems associated with the welding or brazing method and materials. For example, if the welding technique or process is not capable of providing 100-dB construction, the SELDS test will indicate a weld leak.

The SELDS method, to be fully effective, requires that one shield surface be fully accessible to the detector. On some projects, after the installation of the SELDS monitoring

system, permanent finishing materials have been added over the shield, making that portion of the shield inaccessible. This results in a problem when attempting to use the SELDS test in the affected area. For a typical defect, the detector must be located close to the void before an indication of the defect can be seen. For this same defect, if the probe is moved approximately 2.5 cm (1 in) away from the location where the defect indication is seen, the meter and audio indications will sharply decrease. Stud walls covered with gypsum board or a concrete wear slab added over the shield reduces the sensitivity of SELDS testing.

16.3.1.9 Factory inspections and tests. Factory inspections and tests are part of the project HEMP QC responsibility. Specifications for various HEMP protective features and components will require certain factory inspections and tests to be successfully completed before the item can be shipped to the construction site. These components include electrical filter/ESA assemblies, rf shielded doors and access panels, shielded cabinets and enclosures, and WBC protective devices.

Often, the site HEMP QC inspector and the construction agent's representative will monitor the factory tests, particularly if new designs or more complex components are to be used on the project. For normal factory inspections, the local Government inspectors can be utilized to monitor acceptance of the components prior to their shipment to the job site.

16.3.1.10 Shielding effectiveness survey. To provide an adequate degree of assurance that the HEMP shield and POE protective devices are properly assembled, the construction contractor will perform a preliminary performance test immediately following completion of the HEMP electromagnetic barrier. This test is to be performed prior to the installation of interior finishes and equipment. The test is performed using the permanent SELDS test leads, terminal points, and SELDS test cabinets, if installed. If a permanent SELDS test setup is not part of the project, the survey test plan should specify the equipment and connection points.

In addition to the SELDS testing, plane wave shielding effectiveness measurements are required. The shielding effectiveness test procedures are prescribed in appendix A of MIL-STD-188-125.

The contractor is required to correct any deficiencies identified during the test. A complete report should be provided to the Government, fully documenting the results of the test. This test report will also provide the reference data for all future hardness surveillance tests of the facility using the installed SELDS system.

16.3.1.11 Government quality assurance. The QC role and responsibilities of the contractor have been addressed in the above paragraphs. It must be reiterated that the Government (construction agency/installation agency) also has a strong role in ensuring the HEMP hardening integrity for the facility and that the HEMP protection subsystem will continue to achieve its performance requirements over the planned life of the facility.

There have been instances in past HEMP construction programs where a poorly trained contractor incorrectly performed measurements and concluded that a defective hardening device was acceptable. Unfortunately, there have also been cases of intentional misuse of test equipment and fraudulent data. Such situations can be eliminated with active participation in the quality assurance program by knowledgeable Government representatives.

16.3.2 HEMP acceptance testing.

16.3.2.1 MIL-STD-188-125 acceptance test requirements.

> 5.1.3.5 Shield acceptance testing. After completion of the shield and after installation of the POE protective devices, internal equipments, and finish work provided under the construction contract, the shield acceptance test shall be conducted to determine if the facility shield performs in accordance with minimum requirements of figure 1. The test shall be conducted with POEs and their protective devices in a normal operating configuration, using shielding effectiveness test procedures of appendix A. All defects found during the acceptance testing shall be corrected, retested, and shown to provide the required performance before the installation of communications-electronics equipment.
>
> 5.1.3.5.1 Facility shield modifications. If POEs are added or the facility HEMP shield is breached and repaired after acceptance, shield acceptance testing in the affected area shall be repeated.

> 5.1.4.2 Acceptance testing for architectural POE protective devices. Acceptance testing for architectural POE protective devices shall be conducted using shielding effectiveness test procedures of appendix A.

> 5.1.5.1.2 Acceptance testing for mechanical POE protective devices. Acceptance testing for mechanical POE protective devices, including those for piping and ventilation penetrations, shall be conducted using shielding effectiveness test procedures of appendix A.

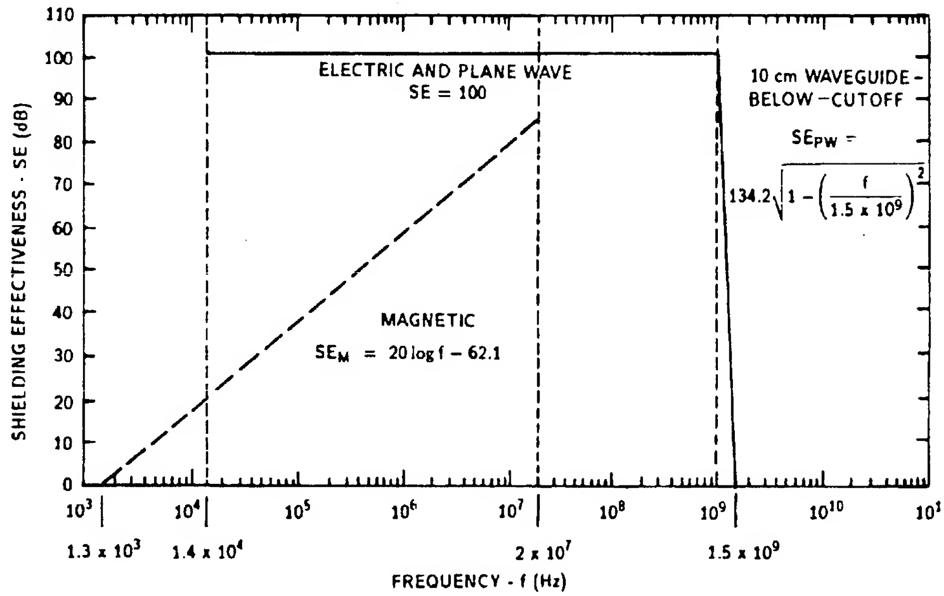


FIGURE 1. Minimum HEMP shielding effectiveness requirements (measured in accordance with procedures of appendix A).

5.1.6.3 Acceptance testing for structural POE protective treatments. Acceptance testing for structural POE protective treatments shall be conducted using shielding effectiveness test procedures of appendix A.

5.1.7.3 Acceptance testing for electrical POE protective treatments. Acceptance testing for electrical POE protective devices shall be conducted using the pulsed current injection test procedures of appendix B.

5.1.8.5 Acceptance testing for special protective measures.

5.1.8.5.1 Special protective measures for mission-essential equipment. Acceptance testing is not required for equipment-level special protective measures installed on MEE in accordance with 5.1.8.1, 5.1.8.2, and 5.1.8.9.2.3. HEMP hardness provided by these special protective measures shall be demonstrated during the verification test program.

5.1.8.5.2 Special protective barriers. Acceptance testing for all special protective barriers shall be conducted using shielding effectiveness test procedures of appendix A. Additionally, acceptance testing for all special protective barriers required because of an electrical POE protective device shall include pulsed current injection in accordance with test procedures of appendix B.

16.3.2.2 HEMP acceptance testing overview. HEMP acceptance tests are conducted to demonstrate that the as-built HEMP shield, POE protective devices, and special protective measures provide the performance required by MIL-STD-188-125. They represent the proof to the Government that the construction contractor has satisfied the contractual obligations.

Acceptance tests will ordinarily be performed at two points in a facility acquisition program, as indicated in the simple life cycle diagram shown in figure 143. The first test period occurs near the completion of building construction, as the host base or using organization takes possession from the construction agency and contractor. The HEMP shield, entryway shields and shielded doors, piping and ventilation penetration protection treatments, and most of the electrical POE protective devices will usually be installed and tested in this phase.

The second acceptance test sequence is conducted following installation and checkout of the mission communications-electronics equipment. This activity may require additional protected points-of-entry to be provided in the barrier for radio antenna lines and other C-E interfaces. Special protective measures may also be implemented on essential equipment outside the barrier or within a special protective volume. Only those hardness critical items supplied under the installation agreement and affected areas of the primary shield are tested at this time. Because of the proximity to the facility hardness verification test, the two sequences may be combined into a single experimental program.

Shielding effectiveness test procedures, contained in appendix A of MIL-STD-188-125 and further discussed in subsection 16.3.2.3, are used to accept the primary and entryway shields, shielded doors and equipment access covers, and HEMP protective elements for mechanical and structural POEs. Performance of the hardening devices installed on penetrating electrical conductors is demonstrated by pulsed current injection measurements, which are described in appendix B to MIL-STD-188-125 and handbook subsection 16.3.2.4.

Both the shielding effectiveness and PCI test methods include provisions for acceptance testing of special protective barriers. When needed, additional acceptance test

requirements appropriate to the particular SPM design should be included in the construction specifications and equipment installation statement of work.

The Government and the contractor are each active participants in the acceptance test program: one of them will actually perform the measurements and the other must be a knowledgeable witness. Specific roles must be defined in the construction specifications. It is strongly recommended that the Government or an independent testing laboratory hired by the Government be the acceptance test conductor.

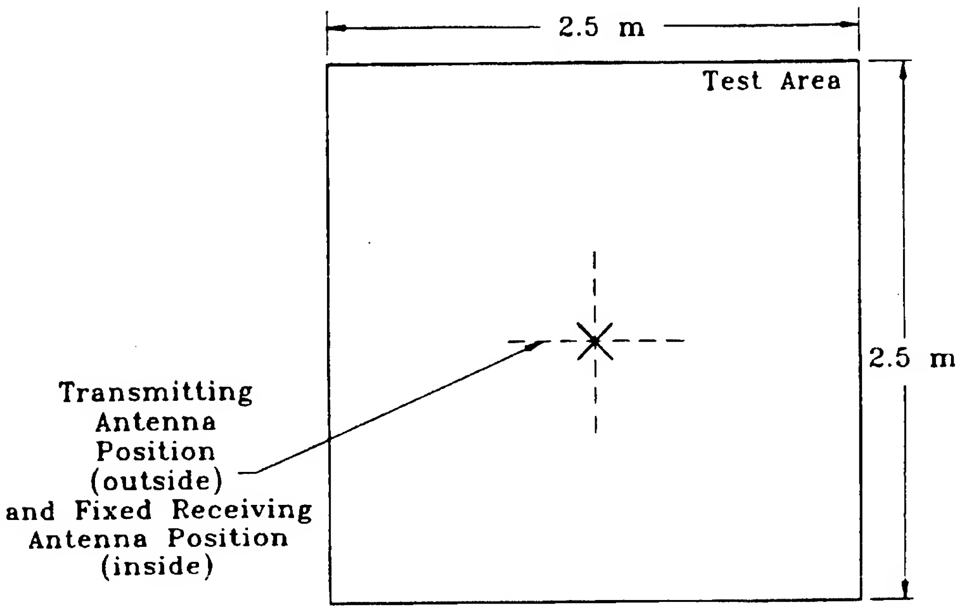
16.3.2.3 Shielding effectiveness acceptance testing. This subsection discusses the use of MIL-STD-188-125 shielding effectiveness test procedures for acceptance testing of the facility primary and entryway HEMP shields, shielded doors and equipment access covers, and HEMP protective devices for mechanical and structural POEs. The testing principles will be briefly described, and information which supplements requirements of the standard will be presented.

16.3.2.3.1 Principles. Electromagnetic fields radiated from a HEMP event (or any other source) interact with a shielded enclosure by inducing currents and charges on its exposed surfaces. When the shield is closed and has no significant defects, leakage to the interior occurs only by diffusion or the skin depth effect. If a shield fault exists, however, other forms of field penetration can take place.

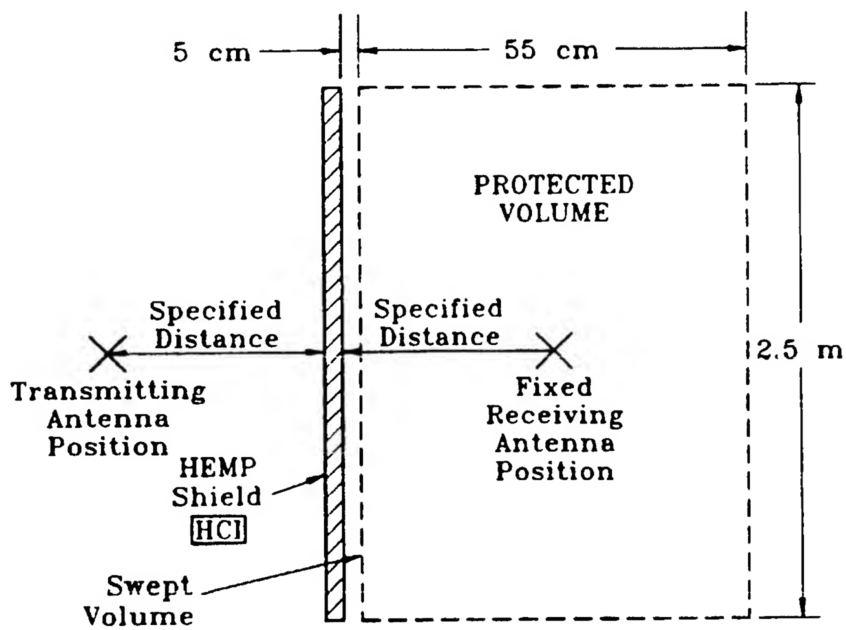
A local transmitting antenna is employed in the MIL-STD-188-125 shielding effectiveness test method to produce the exterior surface current and charge distributions, while a receiving antenna samples the interior electromagnetic environment. It is presumed that the facility HEMP shield material and thickness in skin depths have been chosen to satisfy the required attenuation-versus-frequency criteria. Any failure to meet the MIL-STD-188-125 requirements, therefore, indicates a defect which must be repaired.

Figure 149 shows the shielding effectiveness test geometry in front and side views. The transmitting antenna position is fixed in the center of the test area at the specified distance. Similarly, the fixed receiving antenna location is exactly prescribed. This produces a shielding effectiveness measurement with precisely the same antenna separation that existed when the calibration value was recorded.

However, the fixed antenna position may be nearly 2 m (6.6 ft) from a defect at the corner of the test area. Furthermore, standing waves due to cavity effects or reflections from metal objects in the protected volume can theoretically cause a null point at the fixed measurement location. To increase leak detection sensitivity of the test technique, the receiving antenna is then swept through the 2.5-m x 2.5-m x 55-cm volume shown



a. Front view.



b. Side view.

FIGURE 149. Shielding effectiveness test geometry.

in figure 149. Test area size limitations and the 20-dB excess dynamic range requirement have been chosen in concert to assure an adequate measurement capability everywhere in this volume.

Test frequencies are chosen to obtain approximately one measurement per frequency decade and with consideration given to standard equipment characteristics. The range of values allows site-specific operating frequencies to be avoided. Two transmitting antenna orientations are required because some fault geometries have polarization-dependent response properties.

16.3.2.3.2 Scheduling. The shielding effectiveness acceptance test should be conducted near the end of the construction contract, shortly before the final building inspection, and before installation of the C-E equipment. This timing is dictated by the requirement that all construction contract activities with potential to affect the shield performance must be completed.[6] Examples of such work include the following:

a. All shield panels must be installed and all seam welds must be completed, so that the shield is electromagnetically closed.

b. All POEs and POE protective devices required under the construction contract must be installed and in a normally operating configuration.

c. Internal and external piping and ducts to mechanical POE protective devices, if provided under the construction contract, should be in place and connected.

d. Internal and external wiring to electrical POE protective devices, if provided under the construction contract, should be in place and connected. Wiring in HEMP protective conduits and penetrating fiber optic cables, if provided under the construction contract, must be installed.

e. All heavy equipment and shield wall-mounted panels must be in place.

f. Hangers for the suspended ceiling, light fixtures, or other items should be installed if they interface with a shield surface.

g. Removable wall finishes and corrosion-protection coatings on shield surfaces should be completed.

[6] Final inspection and building transfer may occur with outstanding deficiencies, if those deficiencies do not preclude beneficial occupancy. If any of the listed deficiencies have potential to affect shield performance, it should be noted on the DD Form 1354 that the correction process includes retest of the shield in affected areas.

It is not necessary for installed facility equipment to be operating during the test.

Whenever work that has the potential to affect shield performance must be done subsequent to the construction acceptance test, the affected areas of the shield must be retested. This will often be necessary for correction of construction deficiencies listed on the DD Form 1354, "Transfer and Acceptance of Military Real Property," or as part of the communications-electronics equipment installation effort.

16.3.2.3.3 Facility configuration. There are no facility configuration requirements for shielding effectiveness acceptance testing, except that the HEMP protection subsystem be fully installed and intact.

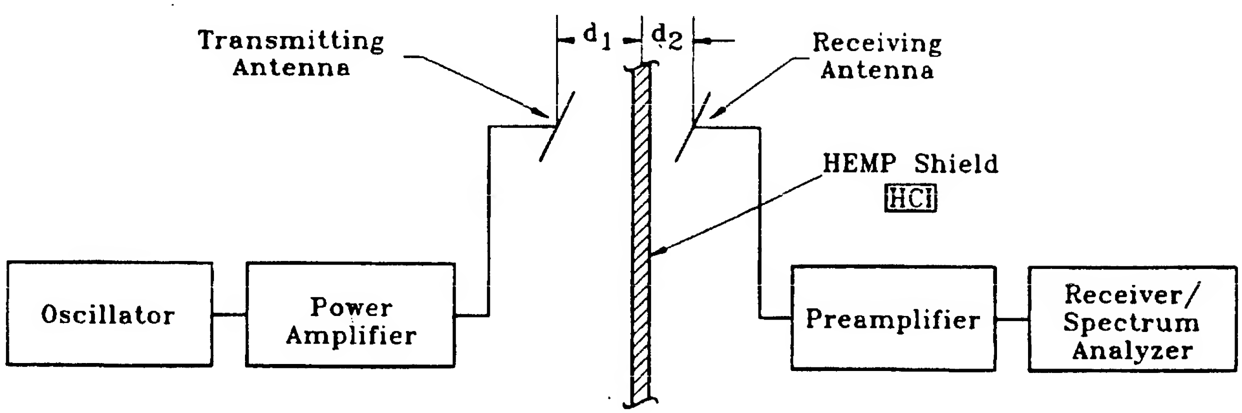
Normal facility equipment may be operating or nonoperating during the measurement sequence. Because a relatively quiet electromagnetic environment at the test frequencies is required in the area of the receiving antenna, however, intense broad-band noise sources must be suppressed. Welding and other arc-generating machines such as electric drills must be shut down. Therefore, some construction or maintenance activities may need to be suspended. The test frequencies may be adjusted to avoid narrow-band emissions.

16.3.2.3.4 Test equipment. Figures 150 and 151, along with table XIV, summarize the MIL-STD-188-125 test equipment requirements and measurement configurations for shielding effectiveness acceptance testing. All hardware items are available from a variety of commercial suppliers.

The oscillator, power amplifier, antennas, preamplifier, and receiver or spectrum analyzer are chosen as a set for each test frequency. The basic criterion for selection is that, with the minimum specified antenna separation, the combination must provide a measurement dynamic range at least 20 dB greater than the shielding effectiveness requirement. For example, assume that the preamplifier/receiver sensitivity is 10^{-6} V or 0 dB μV at a plane wave frequency where the minimum shielding effectiveness is 100 dB. The oscillator/power amplifier/antenna combination must then produce a received signal strength of at least 1 V or +120 dB μV in the calibration configuration, with antenna spacing not less than 2.5 m.

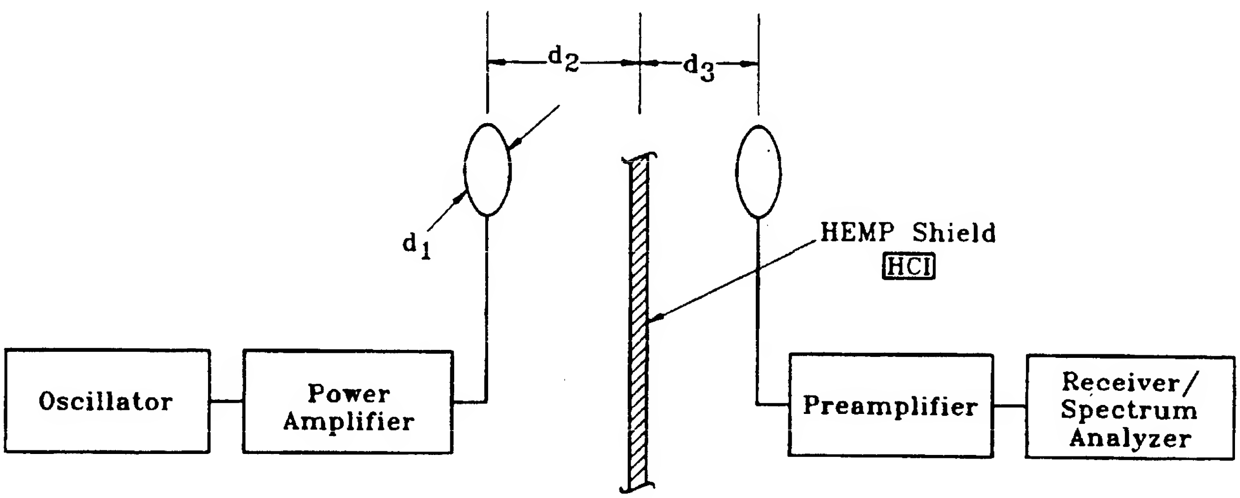
A 50- to 100-W power amplifier may be required at the lowest magnetic field test frequency. An amplifier with 10-W power output (or less) will be adequate at the higher test frequencies, if reasonably efficient antennas are used.

Any antennas which radiate with reasonable efficiency at the prescribed frequencies are acceptable. The most common choices are as follows:



Calibration Spacing $\geq$ 2.5 m
d_1 = Calibration spacing − 30 cm
d_2 = 30 cm (Stationary Measurement)
= 5 cm to 60 cm (Swept Measurement)

FIGURE 150. Plane wave test configuration.



Calibration Spacing $\geq$ 1.25 m
d_1 − Loop diameter
d_2 = Calibration spacing − 30 cm
d_3 = 30 cm (Stationary Measurement)
= 5 cm to 60 cm (Swept Measurement)

FIGURE 151. Magnetic field teat configuration.

TABLE XIV. Shielding effectiveness test equipment requirements.

Equipment	Characteristics (Magnetic Test)	Characteristics (Plane Wave Test)
Oscillator	15-30 kHz, 300-500 kHz, 1-20 MHz	100-400 MHz, 900-1000 MHz
Power Amplifier	15-30 kHz, 300-500 kHz, 1-20 MHz, power output as required for dynamic range	100-400 MHz, 900-1000 MHz, power output as required for dynamic range
Preamplifier	15-30 kHz, 300-500 kHz, 1-20 MHz, amplification and noise figure as required for dynamic range	100-400 MHz, 900-1000 MHz amplification and noise figure as required for dynamic range
Receiver/ Spectrum Analyzer	15-30 kHz, 300-500 kHz, 1-20 MHz	100-400 MHz, 900-1000 MHz
Antennas	15-30 kHz, 300-500 kHz, 1-20 MHz	100-400 MHz, 900-1000 MHz
Miscellaneous Cables and Attenuators	As required	As required

a. A resonant dipole at the lower plane wave test frequency

b. A horn antenna in the 900- to 1000-MHz frequency range

c. Loop antennas for all magnetic field test frequencies

Distances between antennas should be measured from the feedpoint on a dipole, the mouth of a horn, and the center of a loop. For a more complex antenna, such as a log periodic antenna, the tester must ensure that the same point on the structure is used to determine the calibration and measurement spacings.

High-quality, solid-jacketed, coaxial cable and N- or SMA-type connectors should be used in the receive subsystem to minimize electromagnetic interference. If necessary, the receiver/spectrum analyzer can be placed in a shielded enclosure.

It should be noted that shielding effectiveness values are test method-dependent, and significantly different values may be obtained when time-domain or other frequency-domain measurement techniques are used. The results can also vary with the particular equipment, but these differences will remain within acceptable limits when the prescribed calibration and measurement procedures are strictly followed.

A means of communication between personnel inside the protected volume and those outside the barrier must also be provided. Since the HEMP electromagnetic shielding generally precludes the use of hand-held radios for this purpose, a properly protected point-of-entry must be provided.

16.3.2.3.5 Test planning and execution.

16.3.2.3.5.1 Planning. The key to successful and efficient performance of the shielding effectiveness acceptance test is thorough planning. Pretest activities include equipment selection, preparation of the detailed test plan required by the standard, layout of the test areas, and preliminary calibration measurements.

Facility drawings should be obtained and reviewed, and a pretest site visit is strongly recommended. The physical arrangement should be examined during the planning visit, and receiving equipment should be used to identify interfering noise sources and quiet frequencies for testing. A determination whether transmitting antennas will be outside or inside the barrier will be made at this time. Unless there is very sensitive equipment immediately surrounding the barrier or an excessively noisy environment inside the protected volume, transmitters should be placed outside.

Careful advance layout of the test areas is extremely important, because there will be no visual contact between transmitting and receiving antenna locations. Test area boundaries should be sketched on elevation drawings for each wall, the ceiling plan, and floor plan (if access is available). Dimensions for locating test area centers from easily distinguishable features such as building corners, doors, and other penetrations should then be calculated. Thicknesses of interior and exterior finishes should also be determined, so that antennas can be positioned at the correct distances from the shield surface.

A preliminary calibration should be performed before test equipment is shipped to the site to verify that selected instrumentation has the required capability. Calibration spacings and preliminary equipment settings are determined and recorded in this process. The antennas should be mounted on dielectric test stands, and test personnel should be well clear of the antennas when recording readings. Once testing is started, calibration measurements should be repeated at the beginning and end of each test day. The shielding effectiveness instrumentation must also be calibrated before making measurements at unplanned frequencies and immediately after any changes in the equipment. Calibration readings for each specific frequency and configuration should be repeatable within 3 dB. The cause for variations in excess of 3 dB should be determined and corrected, and the calibrations should be redone.

16.3.2.3.5.2 Test execution. Two test teams-one to perform the plane wave measurements and one to make the magnetic field measurements-are recommended. The initial activity in each test day will be to perform the calibrations. The calibration readings should be within 3 dB of the previous results. A suggested sequence for the plane wave test team is then as follows:

a. Set up the first test area for the 100- to 400-MHz stationary measurement in one of the two required polarizations; with the transmitter off, check receiver sensitivity.

b. Energize the transmitter, and record the fixed measurement data.

c. Remove the receiving antenna from the test stand and perform the swept measurement at the same frequency and transmitting antenna polarization. (Additional discussion of the sweeping technique will be presented below.)

d. Rotate the transmitting antenna, and perform the second 100- to 400-MHz stationary measurement.

e. Perform the 100- to 400-MHz swept measurement for the second transmitting antenna polarization.

f. Reconfigure for the 900- to 1000-MHZ test frequency, and repeat the series of four measurements.

An experienced two-man test team will complete the eight measurements for an unobstructed test area in a period of approximately 60 minutes. However, limited or difficult access to shield surfaces can significantly increase testing time.

The magnetic field test team follows a similarly organized sequence. Six fixed measurements and six swept measurements are required in each magnetic test area that contains a POE; only the fixed measurements are taken in magnetic test areas that do not contain a POE. In the former case, the test time per area is approximately 90 minutes.

The transmitting antenna and the receiving antenna for the fixed measurements should be mounted on dielectric test stands. Personnel, test equipment, and other temporary items that might act as electromagnetic reflectors should be kept away from the antennas when recording calibration and test data. It is recognized that installed equipment will frequently prevent precise positioning of antennas as specified in MIL-STD-188-125, appendix A. In such instances, locations as close as practical to those prescribed should be chosen by the test personnel, and the necessary deviations should be noted for inclusion in the test report.

When the barrier is correctly assembled and performing properly, actual attenuation may significantly exceed the minimum requirement and measured signal strength in the stationary configuration should be very nearly equal to the minimum preamplifier/receiver sensitivity reading. If a large received response is observed, the transmitter should be deenergized. Significant decrease of the received signal coincident with the transmitter interruption indicates a probable shield leak, and localization procedures should be initiated. If the received signal remains high, however, an interfering noise signal is present. Either the noise must be eliminated or the test frequency must be adjusted.

To perform the swept measurement, the receiving antenna is removed from the test stand and held with a dielectric rod at least 30 cm (12 in) in length. A dielectric spacer should be attached to the sweeping antenna to assist in maintaining the 5-cm (2-in) distance from the shield. A rapid sweep to locate "hot spots" is made by rotating the polarization and waving the antenna through the specified volume. The highest reading is then found by focusing attention on these hot spots. The sweeping procedure should require no more than four to six minutes to locate the highest reading in the 2.5-m x 2.5-m x 55-cm volume.

If the floor is not accessible for shielding effectiveness measurements, each section of the floor shield should be surveyed with the swept measurement technique when the transmitter is located at a nearby wall test area. While detection of all floor shield defects by this method cannot be guaranteed, major flaws will be found.

The final activity in each test day will be to repeat the calibrations and verify consistency with the previous results.

16.3.2.3.5.3 Special protective volumes. If the volume immediately inside the primary electromagnetic barrier at the area under test is partially or completely within a special protective volume, then additional shielding effectiveness data must be taken. Figure 152 illustrates these supplemental requirements.

The transmitting antenna remains in its normal position, opposite the center of the test area at the appropriate distance. In the protected volume, represented as volume 1 in the figure, the regular fixed and swept (in space) shielding effectiveness measurements are made. Attenuation determined by these data must satisfy the normal requirements for the facility HEMP shield.

The type of measurements performed in volume 2 depends upon size and access. If sufficient room exists, the shielding effectiveness receiving antennas will be used. There is no technique currently prescribed for the case where the special protective volume is too

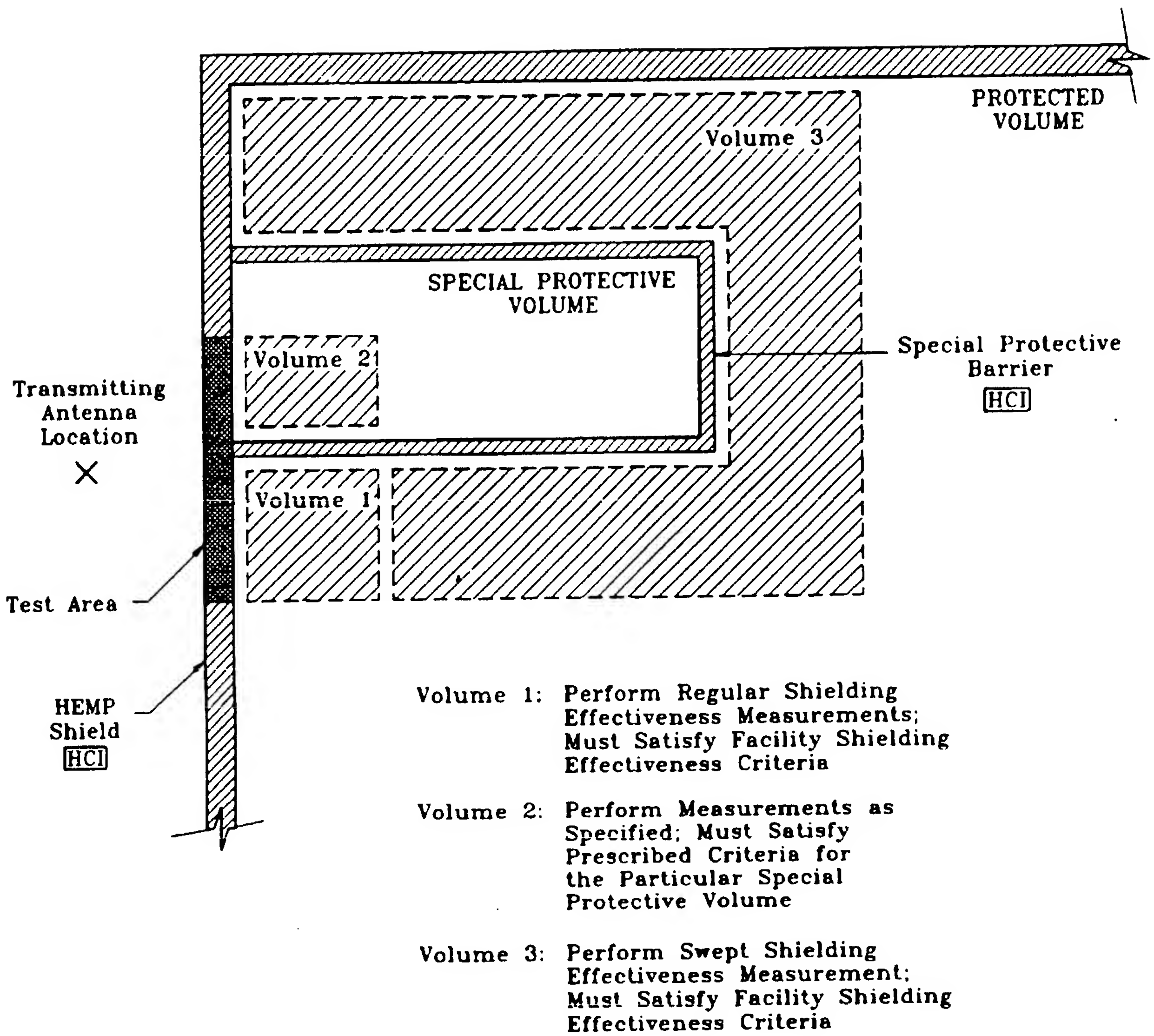


FIGURE 152. Shielding effectiveness measurements for a special protective volume.

small to employ the normal receiving antennas. Efforts aimed at developing a standard procedure that is usable in very small volumes are underway, however, and the services centers of HEMP expertise should be contacted for new information on this subject. In the interim, one possible approach is to install one or more "witness wires" diagonally across the space by bonding them to the barrier at the ends. The current induced on these wires is an indicator of the shielding effectiveness. The sensor type and location must be carefully reported so that the measurements can be repeated at a future time.

Finally, using the normal shielding effectiveness receiving antennas, the entire outer surface of the special protective barrier is sweep-tested. The facility HEMP shield performance requirements apply to these volume 3 measurements.

Note that the special protective volume illustrated in figure 152 spans two test areas. In such an instance, the additional measurements are required when testing each of the areas that are part of the SPV boundary.

16.3.2.3.6 Data recording, format, and disposition. Because no posttest processing other than simple subtraction is required for shielding effectiveness test data, recording may be done either manually or electronically. Electronically recorded data are preferred and are generally more accurate and efficient. When a manual record is kept, the sample data sheet appearing in the standard or any approved form providing equivalent information may be used. Figure 153 illustrates a completed data sheet.

The same type of information must be logged with electronic recording systems. If attenuator settings are not automatically incorporated into the receiver output signal, provisions should be made to insert the setting manually.

As a simple quality control check on the data, fixed and swept shielding effectiveness values for the same test area, frequency, and polarization should be compared. The attenuation measured with the swept procedure should always be less than or equal to that measured in the stationary configuration. Copies of original data sheets must be included in the test report.

16.3.2.4 Pulsed current injection acceptance testing. The second element of HEMP acceptance testing for a ground-based facility hardened in accordance with MIL-STD-188-125 is pulsed current injection. These procedures are used to demonstrate that electrical POE protective devices, as installed, comply with the transient suppression/attenuation requirements of the standard.

SHIELDING EFFECTIVENESS
DATA SHEET

Facility: Site A
Test date: 30 May 1990
Inspector: D. Good

Test Area Number	Type of Test (Plane Wave or Magnetic)	Frequency	Polarization*	Type of Measurement (Stationary or Swept)	Calibration Signal (V_c) (dBμV)	Measured Signal (V_m) (dBμV)	Shielding Effectiveness (dB)	Shielding Effectiveness Requirement (dB)	Pass/ Fail
6	Mag	20 kHz	H	Stat.	+60	+15	≥45	23.9	Pass
6	Mag	20 kHz	H	Swept	+60	+21	39	23.9	Pass
6	Mag	20 kHz	V	Stat.	+59	+15	≥44	23.9	Pass
6	Mag	20 kHz	V	Swept	+59	+20	39	23.9	Pass
6	Mag	357 kHz	H	Stat.	+68	+12	56	49.0	Pass
6	Mag	357 kHz	H	Swept	+68	+17	51	49.0	Pass
6	Mag	357 kHz	V	Stat.	+69	+15	54	49.0	Pass
6	Mag	357 kHz	V	Swept	+69	+21	48**	49.0	Fail
6	Mag	10 MHz	H	Stat.	+108	+18	90	77.9	Pass

Comments: Receiver sensitivities: 20 kHz – +15 dBμv; 357 kHz – +8 dBμV; 10 MHz – +9 dBμV.

**Leakage appears to be at door handle cylinder.

* H → Loop Horizontal
V → Loop Vertical

D Good
Signature

QA, International Testing
Title and Organization

FIGURE 153. **Sample shielding effectiveness data sheet.**

16.3.2.4.1 Principles. A ground-based C³I facility interacts with the HEMP threat environment as one large complex “antenna,” consisting of the structure, the equipment, and all conducting appendages. This "antenna” includes power, communications, and other cables and utility piping such as water, sewer, and fuel lines. Amplitude and frequency content of the response at a given point depend upon the size and physical configuration of the facility; conductivity and other electrical characteristics of the soil; and amplitude, polarization, and angle of incidence of the HEMP fields. Under reasonable worst case conditions, the transient induced on a long, exposed conductor may have an open-circuit voltage of hundreds of kilovolts and a short-circuit current of thousands of amperes.

To protect the mission-essential equipment from such extreme transients, a combination of nonlinear and linear hardening devices as described in section 12 is typically required. The devices must limit residual internal voltage and current stresses to maximums allowed by the standard, while surviving the exposure.

The characteristics of the devices used for protection and the time-domain specification of their performance requirements dictate the type of acceptance testing needed. Low-level excitation approaches are unable to exercise the nonlinear features or demonstrate the ability to withstand reasonable worst case transients and are, therefore, inadequate. The effective technique is threat-like pulsed current injection.

Figure 154 illustrates a wire-to-ground PCI acceptance test of an electrical POE protective device. The pulse generator applies a threat-relatable transient through the coupler to the penetrating conductor at an injection point outside the electromagnetic barrier. The injected current and residual internal current waveforms are recorded as proof of compliance with the transient suppression/attenuation requirement, and device survivability is determined by posttest inspection and measurements. Such a test is appropriate for protection schemes that use current diversion (surge arresters and filters) to divert the HEMP induced current to the outside of the shield.

For the long pulse, however, the filters and the HEMP shield are transparent. Hence the current diversion techniques are not effective in preventing this part of the HEMP-induced response from interacting with circuits and equipment inside the shield. For these late-time transients, current-interrupting techniques are recommended. To test circuit interruption devices, where a shunt path to ground as shown in figure 154 is not present, it is necessary that the source produce the appropriate open circuit voltage and have the source impedance given in section 12. With a current interruption device installed and functioning properly, the currents measured at the locations shown in figure 154 will be

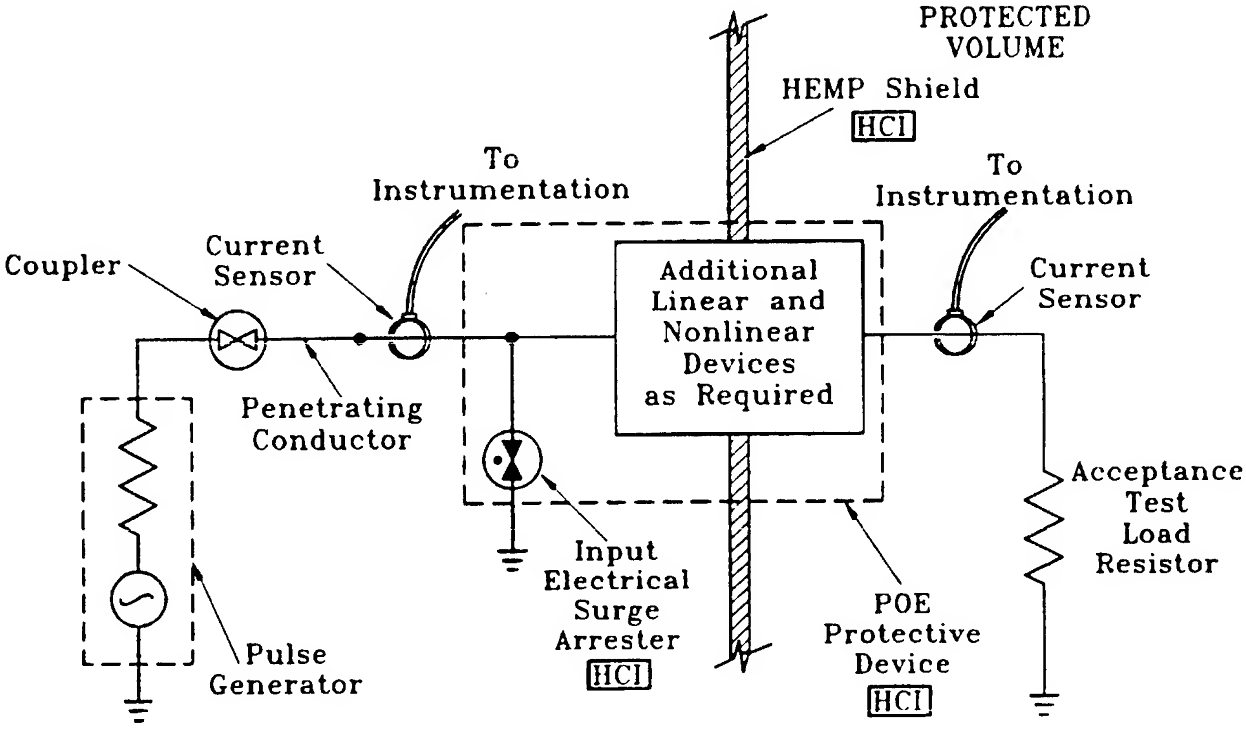


FIGURE 154. PCI acceptance test wire-to-ground configuration.

nearly zero. Nevertheless, test should demonstrate that the device withstands the open-circuit voltage of the long pulse source.

For the protective device to be considered acceptable, specified norms of the residual internal response to the short pulse excitation may not exceed maximum limits prescribed by the standard. Norms that apply and their maximum allowed values vary according to the type of circuit under test.

Tables XV and XVI and figures 155 and 156 are extracted from MIL-STD-188-125, appendix B, and present the required PCI excitation levels and norm pass/fail criteria for acceptance testing. Wire-t-shield, shield-to-ground, and conduit-to-ground procedures in the table are discussed later in this subsection.

The set of PCI tests prescribed by MIL-STD-188-125 and listed in tables XV and XVI will adequately evaluate the electrical POE protection for nearly all installations. If the site has an unusual coupling configuration, however, additional injection tests should be defined by the test organization as needed. In the case of a small antenna mounted on

TABLE XV. PCI acceptance test amplitudes and waveforms.

a. Double exponential waveforms (figure 155).

Class of Electrical POE	Type of Injection	Peak Current - I (A)	Risetime - τ_R (s)	FWHM (s)	Acceptance Test Load Impedance (Ω)
Commercial Power Lines (Intersite)					
Short Pulse	Wire-to-ground[a]	4000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[c] 2 or V_{rated}/I_{rated}
Intermediate Pulse	Wire-to-ground[c]	500	$\leq 1\times10^{-6}$	$\geq 5\times10^{-3}$	50
Long Pulse	Wire-to-ground[a]	200	≤ 0.5	≥ 100	50
Other Power Lines (Intrasite)					
Short Pulse	Wire-to-ground[d]	4000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[c] 2 or V_{rated}/I_{rated}
Audio/Data Lines (Intersite)					
Short Pulse	Wire-to-ground[a]	[d] $8000/\sqrt{N}$ or 500	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	50
Intermediate Pulse	Wire-to-ground[a]	500	$\leq 1\times10^{-6}$	$\geq 5\times10^{-3}$	50
Long Pulse	Wire-to-ground[a]	200	≤ 0.5	≥ 100	50
Control/Signal Lines (Intrasite)					
Short Pulse	Wire-to-ground[a]	[d] $8000/\sqrt{N}$ or 500	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[c] 2 or V_{rated}/I_{rated}
RF Antenna Lines--Signal Conductors					
[e] $f \leq 2$ MHz	Wire-to-shield	8000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[f] 50
RF Antenna Lines--Shield					
Buried[g]	Shield-to-ground[h]	1000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[f] 50
Nonburied	Shield-to-ground[h]	8000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[f] 50
Conduit Shields					
Buried[g]	Conduit-to-ground[i]	1000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[j] 2
Nonburied	Conduit-to-ground[i]	8000	[b] $\leq 1\times10^{-8}$	5×10^{-7} - 5.5×10^{-7}	[j] 2

b. Damped sinusoidal waveforms (figure 156).

Class of Electrical POE	Type of Injection	Peak Current - I (A)	Center Frequency - f_c (MHz)	Decay Factor - Q (Dimensionless)	Acceptance Test Load Impedance (Ω)
RF Antenna Lines--Signal Conductor					
[e] 2 MHz $< f \leq 30$ MHz	Wire-to-shield	[k] 2500	[k] $2 \pm 10\%$	[k] 10 ± 3	[f] 50
[e] 30 MHz $< f \leq 200$ MHz	Wire-to-shield	[k] 900	[k] $30 \pm 10\%$	[k] 10 ± 3	[f] 50
[e] 200 MHz $< f$	Wire-to-shield	[k] 250	[k] $200 \pm 10\%$	[k] 10 ± 3	[f] 50

TABLE XV. PCI acceptance test amplitudes and waveforms (continued).

c. Notes to table XV.

[a]For a wire-to-ground test, each penetrating conductor in the cable is driven with respect to ground, where ground is a point on the facility HEMP shield in the vicinity of the POE protective device.

[b] $\tau_R \leq 1 \times 10^{-8}$ s is a design objective. The minimum requirement is $\tau_R \leq 5 \times 10^{-8}$ s.

[c]Whichever is smaller. V_{rated} and I_{rated} are the maximum voltage and current ratings of the POE protective device, respectively.

[d]Whichever is larger. N is the number of penetrating conductors in the cable.

[e] $f = 150/L$ MHz, where L is the largest dimension of the associated antenna in meters. When $f \leq 2$ MHz, a double exponential pulse is required. When $f > 2$ MHz, a damped sinusoidal waveform is specified. (The equation in MIL-STD-188-125 dated 26 June 1990 is in error and is being corrected.)

[f]Signal conductor terminated to the shield with 50 Ω. The shield conductor is electrically bonded to the facility HEMP shield.

[g]An antenna shield is considered buried when it terminates at a buried antenna and less then 1 m (3.3 ft) of its total length is not covered by an earth or concrete fill. A conduit is considered buried when it connects two protected volumes and less than 1 m (3.3 ft) of its total length is not covered by earth or concrete fill.

[h]For a shield-to-ground test, maximum feasible length of the antenna line shield is driven with respect to ground, where ground is a point on the facility HEMP shield in the vicinity of the POE protective device.

[i]For a conduit-to-ground test, maximum feasible length of the conduit is driven with respect to ground, where ground is a point on the facility HEMP shield in the vicinity of the conduit penetration.

[j]Wiring internal to the conduit is terminated at the installed equipment, if present. Other internal wiring is bundled together and terminated in common 2 Ω resistors at each end. The conduit is welded to the facility HEMP shields at both ends.

[k]The damped sinusoidal waveform is a design objective. The minimum requirement is to inject the current output from a PCI source which delivers the following current pulse $[I(t)]$ with an unspecified waveform into a 50 Ω calibration load:

a. $$\int_0^T I(t)\,dt \geq \frac{0.3\hat{I}}{f_c}$$

b. $$|I(t)| \leq K_{DS}\,\hat{I}e^{-\frac{\pi f_c t}{10}} \quad \text{for all } t > T$$

where t is time in seconds, $\hat{I}$ is the prescribed peak current in amperes, f_c is the prescribed center frequency, K_{DS} is a scaling constant, and T is the time of the first zero crossing or $1/f_c$ whichever occurs earlier.

TABLE XVI. Maximum allowable residual internal response characteristics for acceptance testing electrical POEs.

Class of Electrical POE	Type of Injection	Type of Measurement	Peak Current (A)	Peak Rate of Rise (A/s)	Rectified Impulse (A-s)	Root Action ($A\sqrt{s}$)
Commercial Power Lines (Intersite)						
Short Pulse	Wire-to-ground	Wire current	10	1×10^{6}	1×10^{-2}	1.6×10^{-1}
Intermediate Pulse	Wire-to-ground	Wire current		No damage or performance degradation[a]		
Long Pulse	Wire-to-ground	Wire current		No damage or performance degradation[a]		
Other Power Lines (Intrasite)						
Short Pulse	Wire-to-ground	Wire current	10	1×10^{6}	1×10^{-2}	1.6×10^{-1}
Audio/Data Lines (Intersite)						
Short Pulse	Wire-to-ground	Wire current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
Intermediate Pulse	Wire-to-ground	Wire current		No damage or performance degradation[a]		
Long Pulse	Wire-to-ground	Wire current		No damage or performance degradation[a]		
Control/Signal Lines (Intrasite)						
Low-Voltage Lines[b]						
Short Pulse	Wire-to-ground	Wire current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
High-Voltage Lines[b]						
Short Pulse	Wire-to-ground	Wire current	1.0	1×10^{6}	1×10^{-3}	1.6×10^{-2}

TABLE XVI. Maximum allowable residual internal response characteristics for acceptance testing electrical POEs (continued).

Class of Electrical POE	Type of Injection	Type of Measurement	Peak Current (A)	Peak Rate of Rise (A/s)	Rectified Impulse (A-s)	Root Action ($A\sqrt{s}$)
RF Antenna Lines Receive Only Signal Conductor Drive	Wire-to-shield	Wire current	0.1	No damage or performance degradation[a]		
		Shield current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
Receive Only Shield Drive	Shield-to-ground	Wire current	0.1	No damage or performance degradation[a]		
		Shield current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
Transmit and Transceive Signal Conductor Drive	Wire-to-shield	Wire current	1.0	No damage or performance degradation[a]		
		Shield current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
Transmit and Transceive Shield Drive	Shield-to-ground	Wire current	0.1	No damage or performance degradation[a]		
		Shield current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
Conduit Shields Signal and Low Current Power[c] Buried or Nonburied	Conduit-to-ground	Bulk current	0.1	1×10^{6}	1×10^{-4}	1.6×10^{-3}
Intermediate Current Power[c] Buried or Nonburied	Conduit-to-ground	Bulk current	1.0	1×10^{6}	1×10^{-3}	1.6×10^{-2}
High Current Power[c] Buried or Nonburied	Conduit-to-ground	Bulk current	10	1×10^{6}	1×10^{-2}	1.6×10^{-1}

[a] Pass/fail criteria on internal response waveform norms are not specified for intermediate or long pulse current injection test sequences. Pass/fail criteria on the peak rate of rise, rectified impulse, and action norms are not specified for RF antenna line signal conductors. The pass/fail criteria of no POE protective device damage or performance degradation also applies to PCI test sequences where this note does not appear in the table.

[b] Low voltage control/signal lines are those with a maximum operating voltage < 90 V. High voltage control/signal lines are those with maximum operating voltage ≥ 90 V.

[c] Low current power lines are those with a maximum operating current ≤ 1 A. Intermediate current power lines are those with maximum operating current between 1 A and 10 A. High current power lines are those with maximum operating current ≥ 10 A.

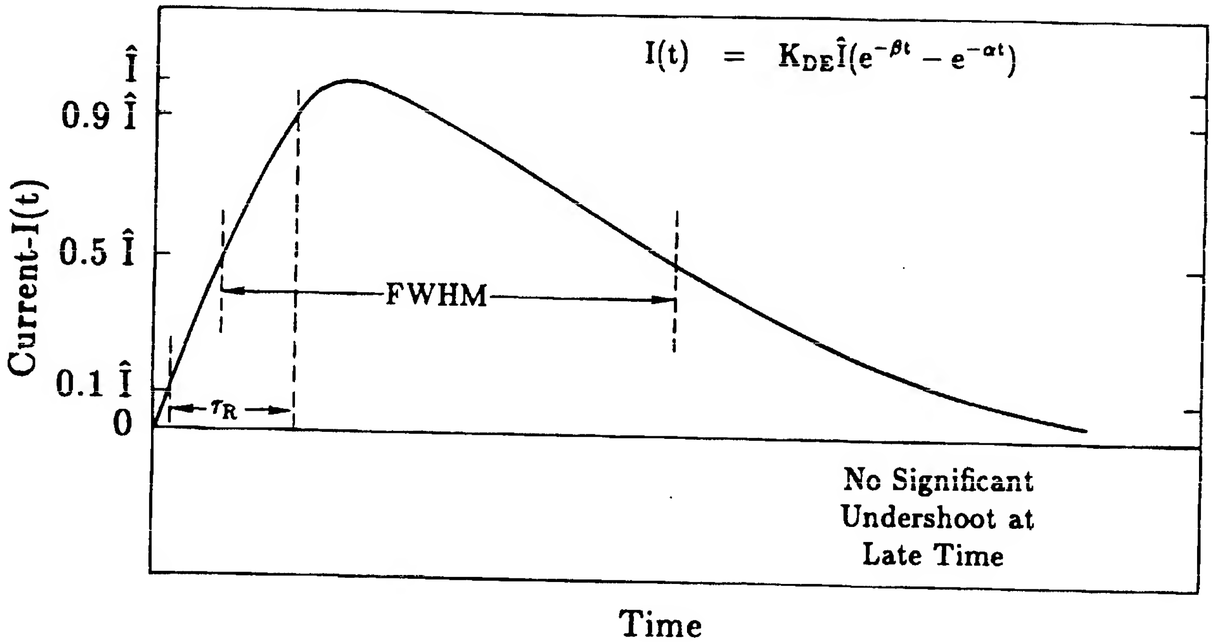


FIGURE 155. Double exponential waveform.

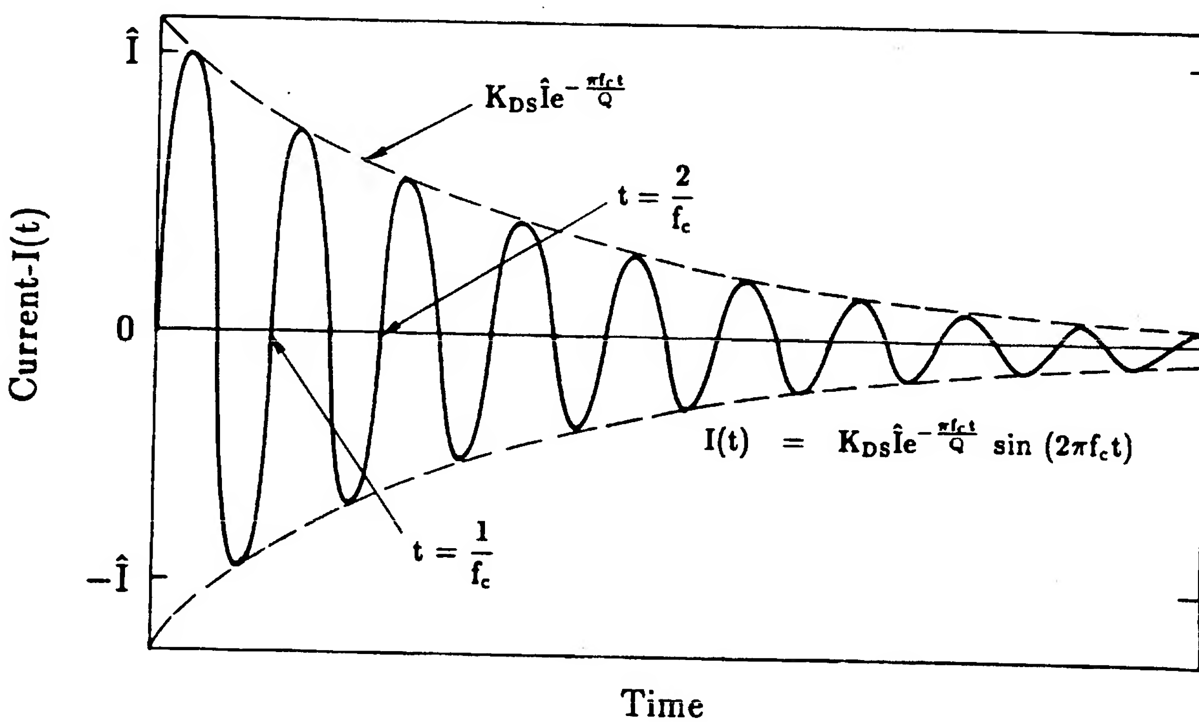


FIGURE 156. Damped sinusoidal waveform.

a tall (>25 m) metal tower, for example, the antenna line core conductor should also be driven with a 500 A short, double-exponential pulse. Similarly, if an intrasite conductor is sufficiently long to have an appreciable intermediate-time response, an intermediate pulse test should also be conducted.

16.3.2.4.2 Scheduling. The PCI acceptance test of an electrical POE protective device can be performed at any time after the device has been installed and the electromagnetic barrier is sufficiently complete in the penetration area to prevent cross-coupling between the external and internal circuits. Testing of those HCIs provided as part of the building construction is usually done near the end of the construction contract for the following reasons:

a. It is convenient to wait until all (or nearly all) devices supplied as part of building construction are in place, so that all PCI acceptance procedures can be performed in a single test period.

b. If the HEMP shield is incomplete, leakage through unfinished sections may contaminate the interior data and provide false indications of excessive residual internal stress.

Relatively few electrical POE protective devices are normally provided with the communications-electronics equipment. Therefore, the PCI equipment installation acceptance testing for this phase should be deferred until all of the HCIs are installed.

If an electrical POE protective device is modified or replaced subsequent to its PCI acceptance test, the acceptance procedure must be repeated.

16.3.2.4.3 Facility configuration. The prerequisite conditions for PCI acceptance testing of an electrical POE protective device are that the device installation must be complete and that the electromagnetic barrier in the vicinity of the point-of-entry must be reasonably intact. The latter condition is required so that the instrumentation signal-to-noise ratio is not excessively degraded.

Equipment which will ultimately be wired to the exterior and interior terminals of the protective device must be disconnected during the PCI acceptance test. Therefore, it is not necessary for that equipment to be present or operable.

16.3.2.4.4 Test equipment. Table XVII is a list of the equipment required for PCI acceptance testing, and figure 157 is a schematic illustration of a typical PCI data recording system. These equipment requirements are discussed below in two parts: simulation sources and sensors and instrumentation.

TABLE XVII. PCI acceptance test equipment requirements.

Equipment	Characteristic		
	Short Pulse	Intermediate Pulse	Long Pulse
Pulse Generators	70-8000 A, double exponential waveform and damped sinusoidal waveform	50-500 A, double exponential waveform	20-200 A, double exponential waveform
Current Sensors (Injected Transient)	10 kHz-750 MHz, 0-8000) A	dc -10 MHz, 0-500 A	dc -10 kHz, 0-200 A
Current Sensors (Residual Internal Transient)	100 Hz-750 MHz, 0-100 A, transfer impedance as required for measurement sensitivity	dc -10 MHz, 0-500 A	dc -10 kHz, 0-200 A
Oscilloscopes or Transient Digitizers	100 Hz-750 MHz, minimum sensitivity as required for measurement sensitivity	dc -10 MHz	dc -10 kHz
Data Recorder	0-5 ms	0-50 ms	0-100 s
Preamplifier	100 Hz-750 MHz, amplification and noise figure as required for measurement sensitivity	—	—
Instrumentation Shield and Power Supplies	As required for isolation from pulse generator	As required for isolation from pulse generator	As required for isolation from pulse generator
Miscellaneous Cables, Attenuators, and Dummy Load Resistors	As required	As required	As required

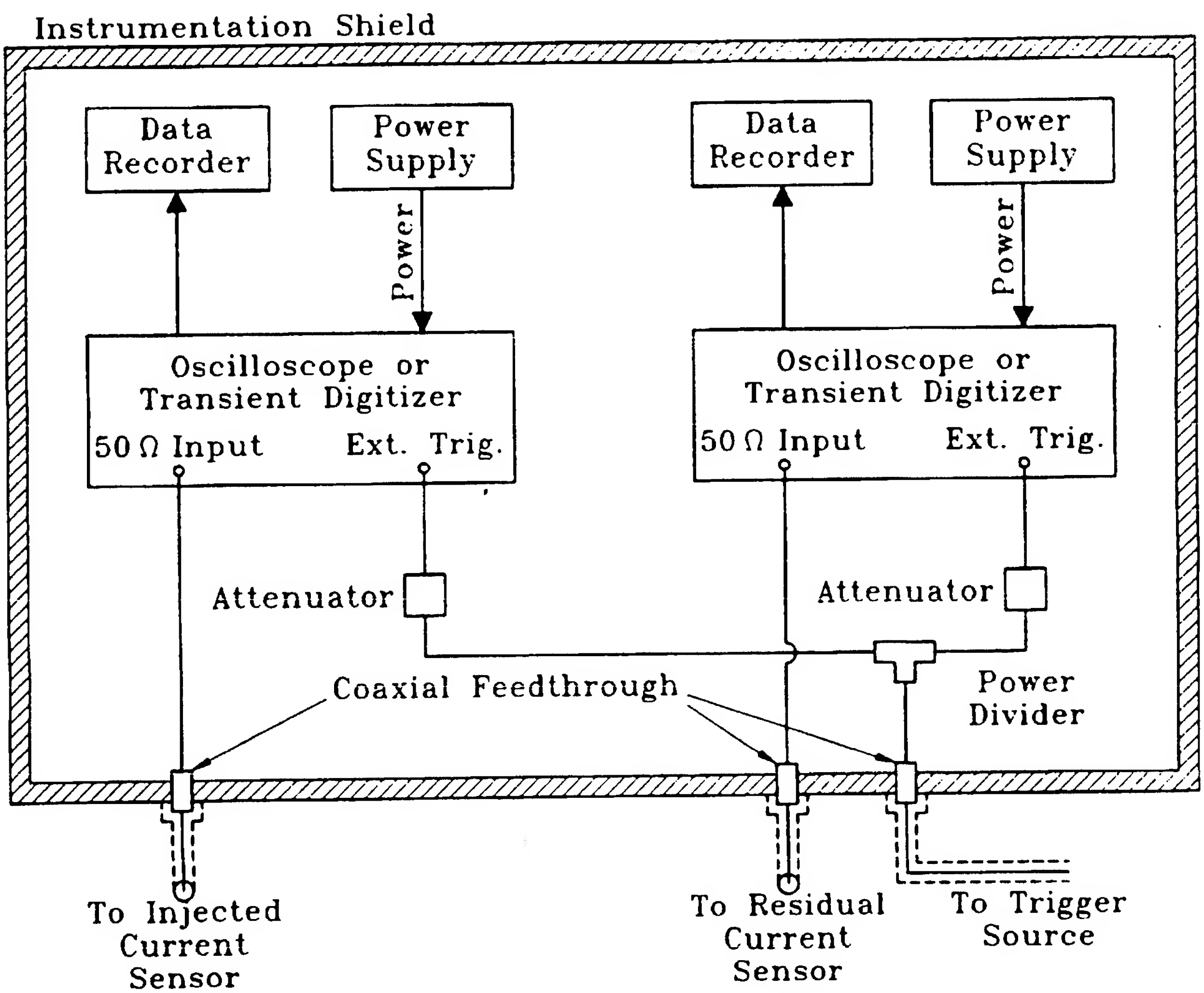


FIGURE 157. Typical PCI data recording system.

16.3.2.4.4.1 Simulation sources. Simulation source requirements for electrical POE protective device acceptance testing are defined in PCI procedures of the MIL-STD-188-125 and are summarized in table XVII. Depending on the classes of hardened electrical penetrations present at a particular site, as many as six different injected current waveforms may be needed.

The short double-exponential pulser [figure 155; $\hat{I} \leq 8000$ A; $\tau_R \leq 10$ ns (design objective), ≤ 50 ns (requirement); FWHM = 500-550 ns] will be required for virtually every facility acceptance test. The intermediate double-exponential source (FWHM ≤ 5 ms) and the long double-exponential pulse generator (FWHM ≤ 100 seconds) are needed at facilities with intersite power line POEs or intersite audio/data line penetrations protected by transient suppression/attenuation devices.

To determine which of the three damped sinusoidal pulse waveforms (see figure 156; $\hat{I} \leq 2500$ A/ $f_c \approx 2$ MHz; $\hat{I} \leq 900$ A/$f_c \approx$ 30 MHz; $\hat{I} \leq 250$ A/$f_c \approx 200$ MHz) are to be used, site antenna lengths must be measured and converted into characteristic frequencies according to the formula:

$$f = \frac{150}{L}\ \mathrm{MHz} \tag{16}$$

In equation 16, L is the physical length in meters for a monopole or dipole. L is the diameter in meters in the case of a loop; in the case of a rhombic antenna, it is the largest diagonal dimension in meters. For more complicated geometries, L is the maximum distance in meters between any two points on the active elements of the antenna. The computed frequency f provides the entry into the "Class of Electrical POE" column in table XV.

The PCI requirements are stated in terms of current delivered to the POE protective device (rather than current delivered into a short circuit or calibrated load). In order to ensure that pulse generator output is not significantly influenced by the device under test, the following source impedance guidelines should be observed:

a. The short double-exponential pulser should have approximately 70 Ω source impedance.

b. The intermediate double-exponential and 2 MHz damped sinusoidal pulsers should have approximately 50 Ω source impedances.

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[7]The characteristic frequency equation in MIL-STD-188-125 dated 26 June 1990 is in error and is being corrected.

c. The long double-exponential pulser should have approximately 5 Ω source impedance.

d. The 30 MHz and 200 MHz damped sinusoidal pulses should have source impedances approximately equal to the characteristic impedance of the antenna feed cable.

Although other methods of coupling are possible and will be discussed later in this section, the pulse generator output will normally be directly coupled to the penetrating conductor for acceptance testing.

Prototype pulsers and couplers capable of delivering the required double-exponential waveforms have been built for the Defense Nuclear Agency. Sources for PCI testing of rf antenna lines are still under development. Until these simulators are offered by commercial suppliers as standard products, it is recommended that pulsers/couplers be provided to the acceptance test organization as Government-furnished equipment.

16.3.2.4.4.2 Sensors and instrumentation. Key parameters in selection of the data acquisition equipment are bandwidth, sensitivity, and required length of the data record. Aperture size and saturation characteristics of current sensors, particularly for PCI verification testing to be addressed later in this section, are also important factors. Instrumentation with the desired performance can generally be obtained from various commercial sources.

At the present time, it is difficult to find a single inductive current probe or current viewing resistor which simultaneously meets bandwidth specifications and all other requirements for MIL-STD-188-125 PCI testing. However, currents can be measured by using multiple sensors that, in combination, cover the required frequencies.

The injected-current sensor must have a sufficiently small transfer impedance to measure the peak value of the driven transient. For the intermediate and long pulse tests, the same type of probe can be used for both the injected transient and the residual internal response.

In the short pulse tests, residual internal responses may be as small as a few milliamperes. Sensors compatible with these smaller signals must therefore be chosen. For a probe with the appropriate transfer impedance, preamplification will seldom be necessary.

In terms of cycle times at the highest response frequencies, record lengths specified for MIL-STD-188-125 PCI testing are very long. This implies that data must be taken at

[1]It is not necessary for the sensor to be "flat" over the entire range of frequencies; corrections for frequency-dependent transfer functions can be incorporated into the data processing algorithms.

two or more sampling rates in order to capture the response over the entire period, while preserving the capability to resolve the earlier time/higher frequency behavior.

Nearly real-time data processing is essential for efficient PCI testing, because of the need to assess each response before proceeding to the next higher injection level. Therefore, computerized acquisition and preprogrammed analysis routines are strongly recommended.

Depending on the level of system noise at the facility under test, the radiation characteristics of the PCI pulse generators, and the relative locations of the sources and instrumentation, shielding of the data acquisition equipment and isolation of the associated power supplies may be required. Because of this uncertainty, the tester should plan to provide shielding and power isolation.

Finally, injected current sensors are placed at locations outside the barrier and residual current sensors are located inside the protected volume. The instrumentation will normally be housed in a van outside the building. Whether the oscilloscopes and digitizers are outside or inside, however, it will usually be necessary to pass test signals through the shield. In order to meet the testability requirements of MIL-STD-188-125, test penetrations are needed. This topic is addressed in section 17.

16.3.2.4.5 Test planning and execution.

16.3.2.4.5.1 Planning. Planning for a PCI acceptance test is straightforward. Requirements set by the standard for the detailed PCI acceptance test plan and procedures document can be used as a checklist for pretest activities.

A pretest site survey is recommended to examine the physical layout of the facility and to determine locations where pulsers and instrumentation can be placed. Devices to be tested should also be inspected to select the injection points, sensor locations, and installation configurations for acceptance test load resistors.

For purposes of establishing the schedule, it can be estimated that an experienced test team will complete three to five PCI sequences (a sequence is one pulse type for one transient suppression/attenuation device) per day. A somewhat higher rate can be achieved when testing a series of identical devices. This assumes a near-real-time data processing capability for evaluating residual internal response norms before proceeding to the next injection level.

A two- or three-man test team will be required, depending on the degree of automation of the pulsers and instrumentation. The team members can increase efficiency by working

in parallel. One team member prepares the next circuit to be tested and inspects and performs the surge arrester measurements on devices for which the PCI sequence has been completed. The remaining member (or members) operates the pulser and data acquisition equipment.

The pulse generators should be checked in the laboratory with devices similar to those that will be tested on-site to verify proper characteristics. Preliminary calibrations and transfer function measurements should be made for sensors and other instrumentation elements.

16.3.2.4.5.2 Test execution. The type of current injection applicable to PCI acceptance testing on most penetrating conductors is the wire-to-ground configuration, previously illustrated by figure 154. The following discussion focuses on a wire-to-ground test. Variations for wire-to-shield, shield-to-ground, and conduit-to-ground configurations will be addressed at the conclusion of this subsection.

The PCI test consists of a series of current injections at increasing amplitudes as described in MIL-STD-188-125, rather than a single pulse. There are two principal reasons for performing this sequence:

a. To gradually approach the maximum drive level, thereby minimizing risk of damage to the POE protective device (and to connected equipment during verification testing).

b. To measure the maximum residual internal stress; this may not occur at maximum excitation because of POE protective device nonlinearities.

The steps for conducting the PCI acceptance test sequence in appendix B of MIL-STD-188-125 are quite explicit and should be carefully followed. After setting up the pulse generator and data acquisition equipment and performing calibrations in accordance with the detailed test plan, sensors are installed and a noise immunity check is conducted. The test configuration is then established, and the first pulse is injected at the lowest available output of the pulse generator or at 10 percent of the maximum amplitude, whichever is greater.

The injected current and the residual internal response current are measured for every pulse. Before proceeding to the next higher injection level, the data must be analyzed in near-real time to evaluate compliance with requirements. This sequence of pulse injection and data analysis is continued until the prescribed maximum excitation has been delivered.

After the last pulse, the POE protective device should be carefully inspected for damage or degradation. Signs of possible failure include uncontained arc strikes, case deformation or leakage, and insulation discoloration or puncture. The characteristics of the input surge arrester are also checked against device specifications and measured before and after PCI testing. The ESA check is performed by connecting a dc power supply across the device through a current-limiting resistor and slowly increasing the voltage. The dc breakdown voltage for a spark gap or varistor voltage at 1 mA dc current is recorded and must be within the manufacturer's design range. The final step is to remove all test connections and to restore the original circuit configuration.

The wire-to-shield configuration for testing coaxial rf antenna lines is depicted by figure 158. This arrangement is topologically identical to the wire-to-ground test. In practice, the only significant differences are that the injected current sensor and core wire response current sensor should be coaxial probes, and the acceptance test load resistor should be a coaxial terminator.

Shield-to-ground and conduit-to-ground PCI acceptance testing configurations are shown in figure 159. Ideally, the prescribed transient is driven over the entire length of the conduit or shield. This is seldom possible, however, because frequency-dependent attenuation of the driven conductor and shield leads to erosion of the leading edge of the injected pulse. The maximum length ℓ which results in an injected pulse risetime $\leq$ 50 ns should therefore be excited. To obtain the largest possible value of ℓ, the following actions should be taken:

a. Remove all intermediate grounds and other low-impedance shunts along the conduit or shield run, if possible.

b. Carefully configure the pulse generator return conductor so that it forms a low-impedance, two-conductor transmission line with the conduit or shield under test.

It should be possible to experimentally determine ℓ with a few preliminary pulses. The driven length should be recorded for use in future testing.

16.3.2.4.5.3 Special protective volumes. When the POE protective device under test enters a special protective volume, additional response measurements are specified in MIL-STD-188-125. Signal amplitudes and waveforms on conductors that penetrate into the protected volume through the special protective barrier are also recorded as shown in figure 160. Pass/fail criteria for these measurements are the MIL-STD-188-125 residual stress norm limits applicable to the type of circuit being monitored (rather than those for the class of electrical POE that is being driven).

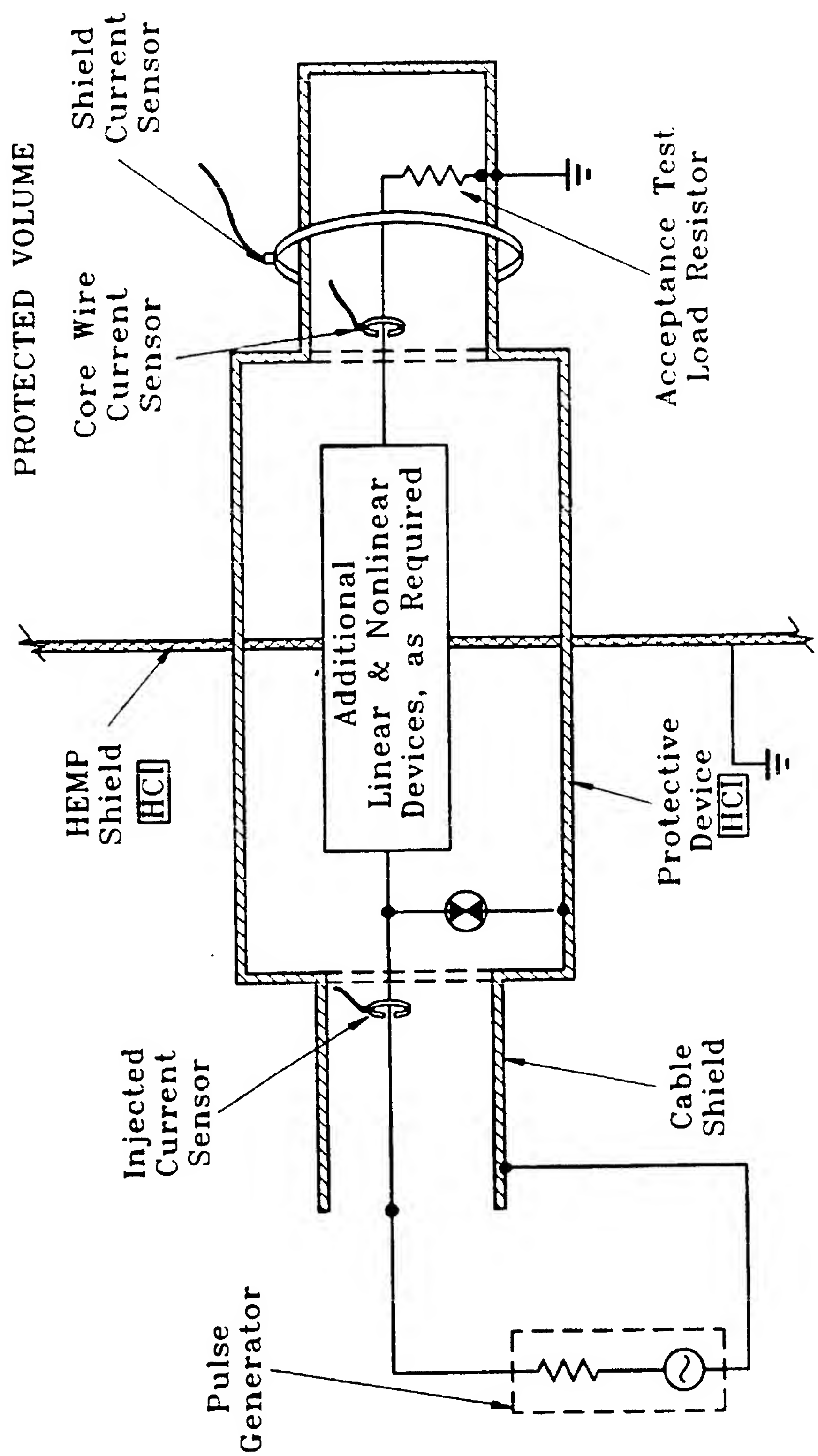


FIGURE 158. PCI wire-to-shield acceptance test.

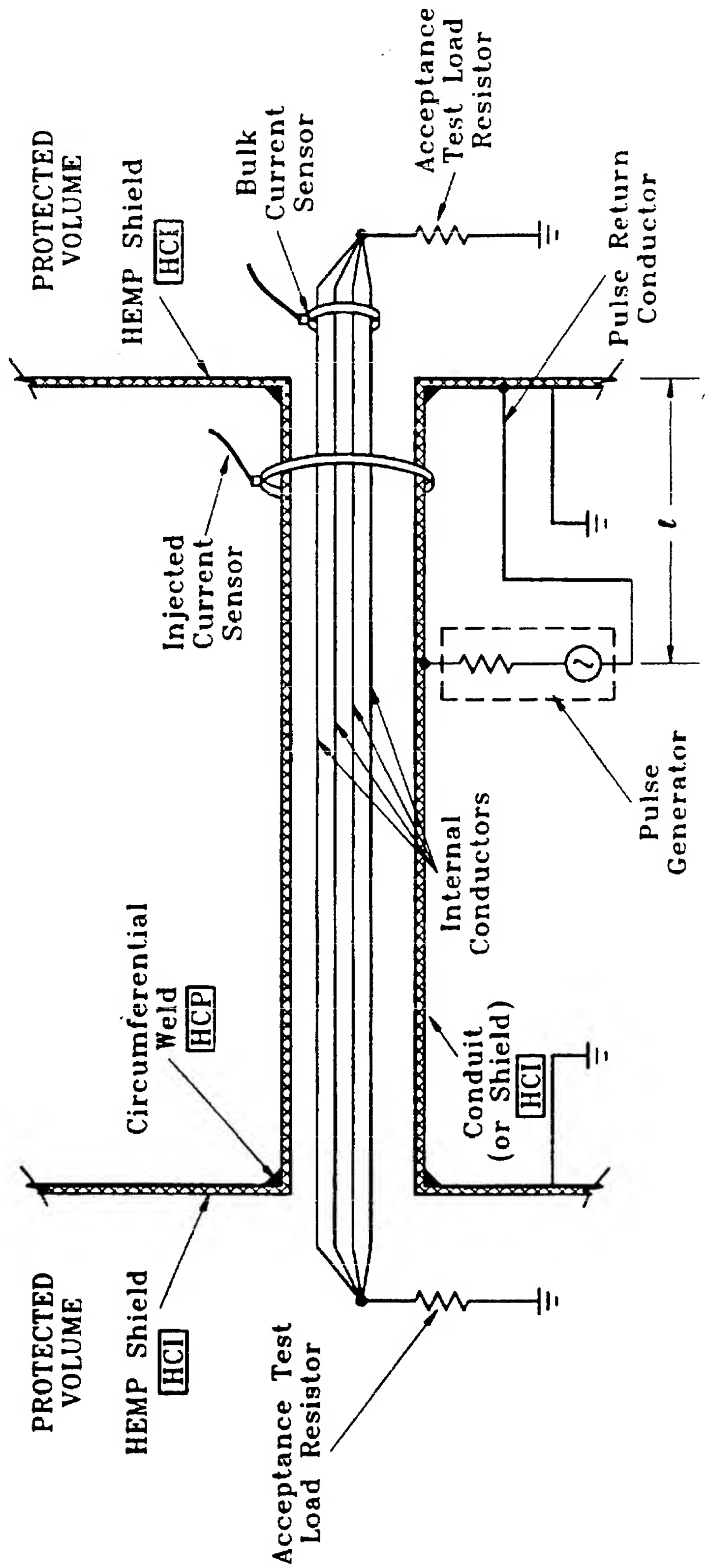


FIGURE 159. PCI conduit-to-ground acceptance test.

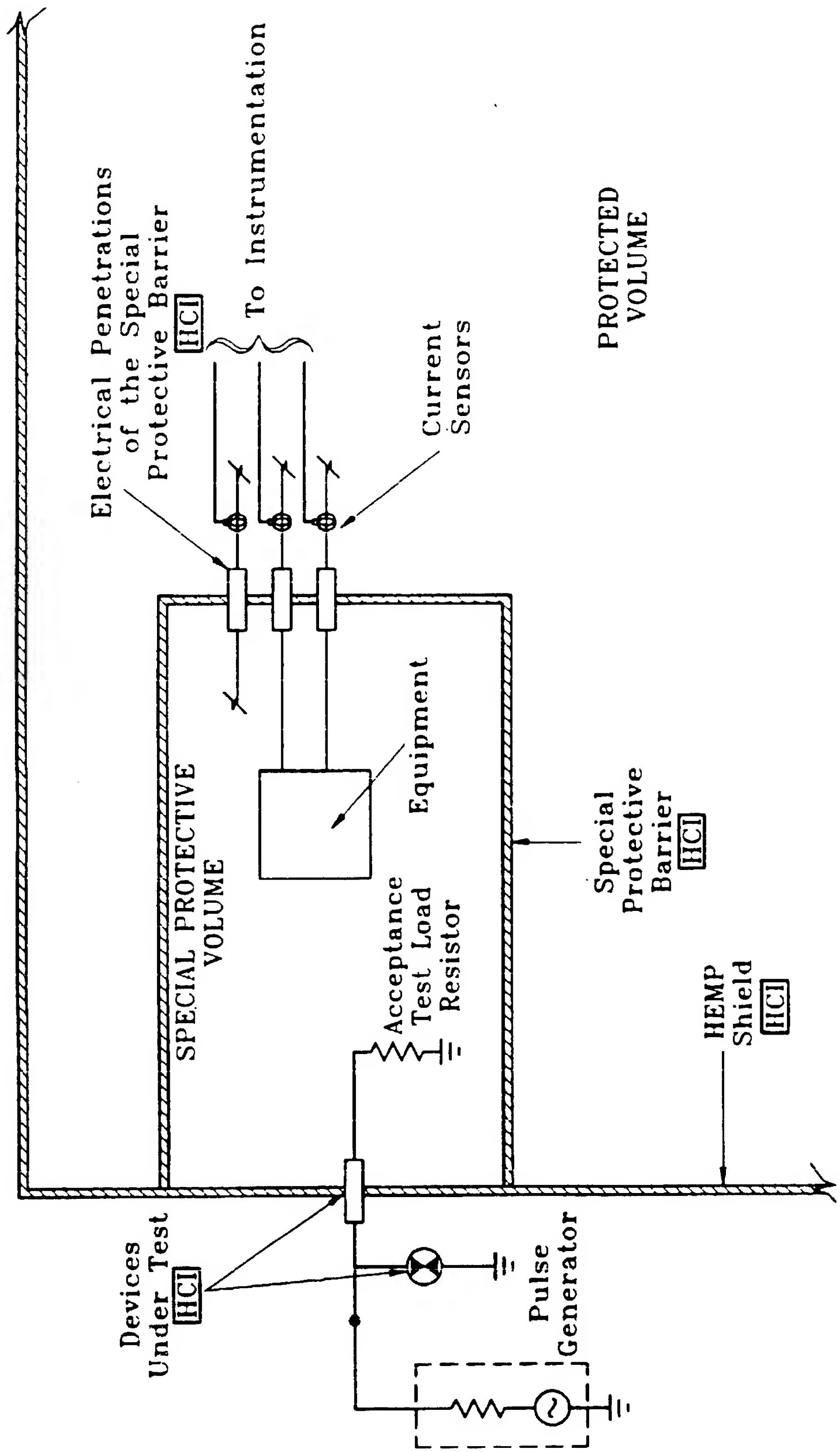


FIGURE 160. Additional PCI measurements for a special protective volume.

When the possibility of significant cross-coupling is remote because of large distances (in excess of 1 m) between the device under test and other wires in the special protective volume, the supplemental acceptance test measurements may be omitted with approval of the sponsoring Government agency. However, such waivers should not be granted during PCI verification testing.

16.3.2.4.6 Data recording, format, and disposition. For reasons that are discussed earlier in this section, automated data acquisition is strongly recommended for PCI testing. Data should be stored on the media and in the format specified in the test plan with complete identification that includes, but is not limited to, the following items:

a. Facility

b. Date and time of data acquisition

c. Test configuration (or test sequence number, when the configuration is defined in the test plan)

d. Test point location

e. Type of measurement

f. Excitation conditions

g. All information (e.g. sensor and instrumentation identification, equipment settings, etc.) required to convert the raw data into engineering units

At the completion of the test program, a complete set of data should be delivered to the sponsoring Government agency. Read-only optical storage disks are generally preferred. They shall be accompanied by narrative or software documentation of the data formats, file structures, and other information necessary for accessing and analyzing the records.

Note that MIL-STD-188-125 also requires that a complete set of the measured results be provided in the acceptance test report. The hard copies are used for visual comparison of future surveillance test data with these baseline measurements. They also provide assurance that the data will be available in archives if problems in reading the disks develop.

16.3.3 Hardness verification testing.

16.3.3.1 MIL-STD-188-125 verification test requirements.

5.1.14 Verification testing. After the HEMP protection system has been accepted and facility equipment is installed and operational, a verification test program shall be conducted. As a minimum, verification testing shall include continuous wave (CW) immersion testing of the electromagnetic barrier, PCI tests at electrical POEs, and additional site-specific tests as needed to demonstrate effectiveness of special protective measures. All deficiencies identified by the verification test program shall be corrected, retested, and shown to provide the required hardness.

5.1.14.1 CW immersion testing. C W immersion testing shall be performed in accordance with procedures of appendix C. At frequencies where the measurement dynamic range exceeds the attenuation required by figure 1, ratios of illuminating field strength to the internal field measurements shall be equal to or greater than the minimum shielding effectiveness requirement. Internal field measurements shall be below the instrumentation noise or operating signal level in frequency bands where measurement dynamic range is less than attenuation requirements of figure 1. Internal current measurements, when extrapolated to threat using equations defined in appendix C, shall be less than 0.1 A. No interference with mission-essential communications-electronics or support equipment shall occur.

When approved by the sponsoring agency for the verification test, a thorough program of shielding effectiveness measurements using procedures of appendix A and a thorough SELDS survey in accordance with MIL-HDBK-423 guidance may be performed in lieu of the CW immersion test.

5.1.14.2 Pulsed current injection verification testing. PCI verification testing shall be performed in accordance with procedures of appendix B. Residual internal transient stress measurements shall not exceed maximum limits for the applicable class of electrica/ POE. POE protective devices shall not be damaged or degraded by the PCI excitations. No time-urgent, mission-aborting damage or upsets of MEE shall occur.[6]

[6]The determination whether an observed interruption or upset is mission-aborting is the responsibility of the operational authority for the facility.

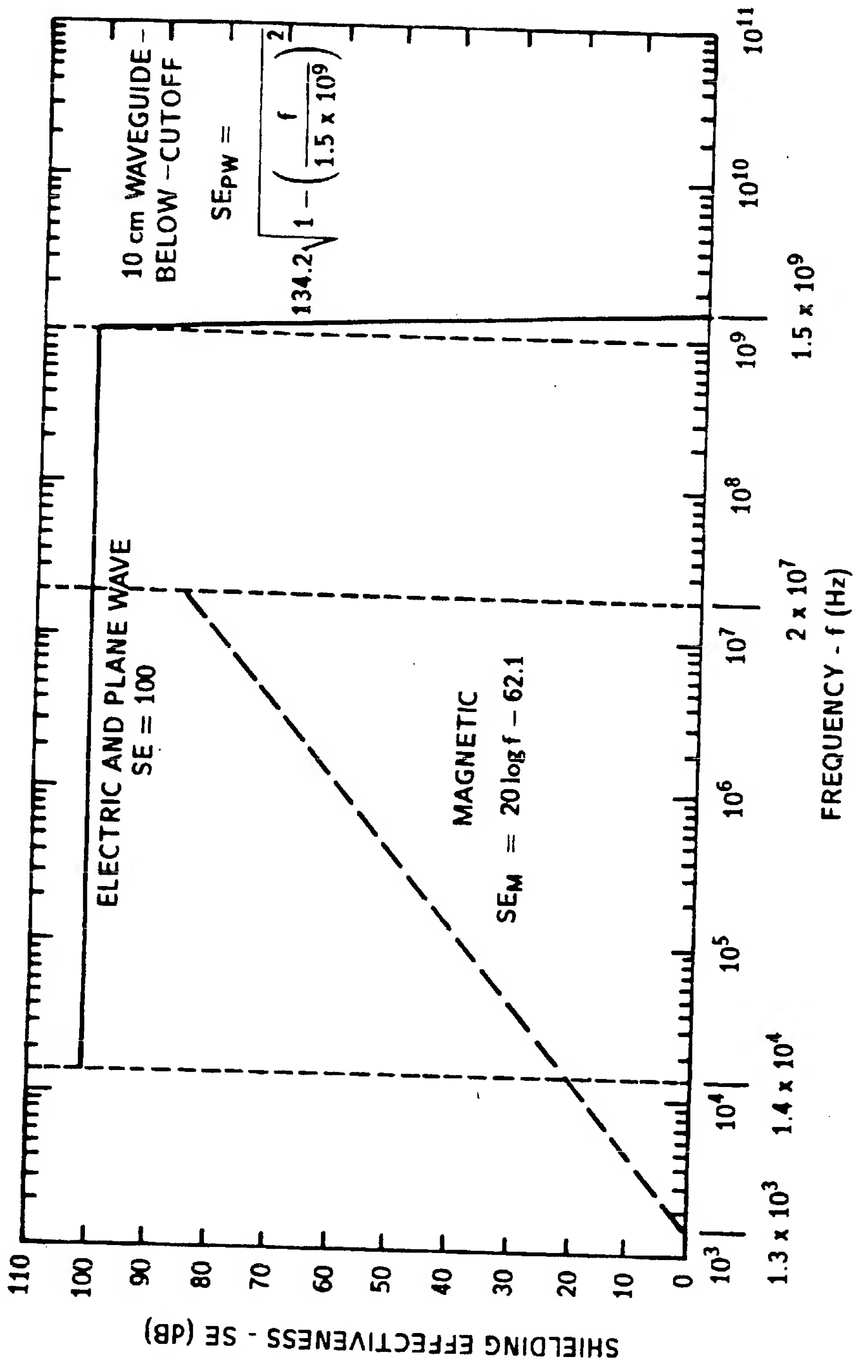


FIGURE 1. ***Minimum HEMP shielding effectiveness requirements (measured in accordance with procedures of appendix A).***

5.1.14.3 Verification for special protective measures. Site-specific procedures for verification of special protective measures shall be developed based upon test approaches of 5.1.14.3.1 and 5.1.14.3.2. The verification testing shall demonstrate that HEMP-induced electromagnetic stresses resulting from facility exposure to the threat environment of DoD-STD-2169 will not cause time-urgent, mission-aborting damage or upsets.[6]

5.1.14.3.1 Verification of special protective measures for mission-essential equipment. Verification testing for MEE hardened with special protective measures shall generally include coupling measurements and pulsed current injection procedures. The coupling test shall be threat-level illumination, threat-level skin current injection, or threat-relatable testing such as CW immersion (see appendix C). MEE cable currents shall be measured and shall be extrapolated to threat when required.

Long conductors, which connect to the MEE and are directly exposed to the HEMP environment, shall be PCI tested with injected pulses of the amplitudes and waveforms prescribed in appendix B.

Cables, which connect or are internal to the MEE and are not directly exposed, shall also be PCI tested. The injected pulse characteristics shall comply with one of the following requirements:

a. Amplitudes equal to 10 times the (measured or extrapolated) threat responses and waveforms similar to the measured data

b. Amplitudes and waveforms prescribed in appendix B for the applicable class of electrical circuit

These verification test excitations shall not cause time-urgent, mission-aborting damage or upset of MEE.[6]

5.1.14.3.2 Verification of special protective barriers. Verification of special protective barriers shall include PCI testing of all electrical POEs which penetrate into the special protective volume from outside the protective volume. Amplitudes and waveforms of the injected pulses shall be as prescribed in appendix B. In addition to functional observations and measurements required by 5.1.14.3.1, residual internal stresses shall be measured on conductors which penetrate from the special protective volume into the protected volume. Responses measured at test points within the protected volume shall not exceed maximum allowable limits, and the test excitations shall not cause time-urgent, mission-aborting damage or upset of MEE.[6]

16.3.3.2 Verification test overview. The purposes of the verification test are to demonstrate the effectiveness of the HEMP protection barrier and to demonstrate the ability of the mission-essential equipment at the facility to continue operating satisfactorily during and following excitation at up to full threat levels (reference 16-2). The HEMP barrier is effective if the protective barrier elements are not damaged as a result of testing and if the residual fields and currents inside the barrier are within the ranges allowed by MIL-STD-188-125. Satisfactory operation of the mission-essential equipment is to be judged on the basis of the functional response of the equipment to the verification test excitations (pulsed current injection and cw immersion). Unlike the acceptance tests, the verification test is performed after all equipment is installed and operating. For the verification test, the load impedances on the electrical POEs are the actual system impedances, and evaluation of the performance of the internal equipment is a key part of the test.

Residual vulnerabilities, if they exist, are not likely to be identified in the course of routine operation of a system. This is because important features of the HEMP environment, including the rate of rise and spatial distribution of the HEMP fields, are not imposed on the system during routine operation. In this regard, HEMP differs from conventional electromagnetic threats such as lightning and electromagnetic interference. These conventional threats may be imposed on the system from time to time. In providing protection against these threats, the common practice is to apply a judicious amount of protection and to rely on information provided in the course of routine operation to determine whether additional hardening measures are required.

In the case of HEMP, if the system were to be subjected to the actual environment, it would be too late to take advantage of the information that would be provided. If HEMP vulnerabilities are to be identified so that they can be eliminated, special measures need to be taken. System level testing is potentially the most reliable approach to identifying residual HEMP vulnerabilities. System level testing has proven effective as a means of identifying HEMP vulnerabilities in the course of many system test programs (reference 16-3). However, whether a testing program will be successful in identifying all of the important vulnerabilities in a system depends on the quality of system excitation and response observation that is applied and the thoroughness with which the verification tests are carried out. MIL-STD-188-125 mandates a hardening design that lends itself to thorough hardness verification testing.

The major features of the required verification testing are identified in this subsection; guidance for implementing the tests is presented in the subsection that follows.

The verification testing required by the protection standard consists of the following elements:

a. Verification of shielding effectiveness of the HEMP barrier. The purpose behind this step is to establish that the shielding effectiveness of the shield component of the HEMP barrier is sufficient to preclude significant HEMP-induced signals from reaching mission-essential equipment inside the barrier other than through the recognized penetrating conductor POEs. Two alternative means of verifying shielding effectiveness are allowed by the standard:

- cw immersion as outlined in appendix C of the standard and explained in 16.3.3.3, or
- With the approval of the sponsoring agency, a MIL-STD-188-125 shielding effectiveness test as described in appendix A of the standard and explained in 16.3.3.4, together with a thorough SELDS survey.

b. Excitation of each of the penetrating conductor POEs just outside the HEMP barrier by PCI techniques as described in appendix B of the standard and explained in 16.3.3.5. The PCI-induced stresses are to conform to the waveforms specifications of the standard and are to be driven at several levels up to the maximum levels indicated in MIL-STD-188-125.

c. Observation of the residual stress levels induced just inside the barrier, the status of the protection elements after testing, and the functional response of the mission-essential equipment.

d. Excitation of equipment protected by special protective measures to either conducted transient stresses up to ten times the worst case levels expected as a result of HEMP coupling to the equipment or to the corresponding amplitudes and waveforms specified in appendix B for the applicable class of electrical circuit and conductor. The worst case levels of excitation of MEE are to be determined by coupling measurements and extrapolation of observed current stresses to threat level. Among the allowed coupling test methods are: threat-level pulsed field illumination, threat-level skin current injection, and cw immersion. The verification procedures for special protective measures are explained further in 16.3.3.6.

e. Formulation of a hardness statement in accordance with the pass/fail criteria of the standard and as explained further in 16.3.3.7.

16.3.3.3 Continuous wave immersion tests. The MIL-STD-188-125 hardness verification procedure is based on the assumption that the HEMP hardness of equipment located in well-shielded enclosures can be determined by pulse current injection testing at the penetrating conductor POEs in the shield, i.e., that the penetrating conductors are the principal HEMP coupling paths to internal equipment. Local excitation tests, such as

shielding effectiveness measurements (see 16.3.2.3), are one method of verifying the validity of this assumption. The cw immersion procedure of appendix C of MIL-STD-188-125, which employs a more global excitation of the HEMP barrier, is another technique for accomplishing this objective.

To the extent that the cw immersion test fields approximate plane waves and the system responds linearly to HEMP excitation, the cw immersion test responses are threat-relatable. Thus, they form a basis for estimating the stresses that would be induced by HEMP in the system. In any practical test, there will be errors in the test-based estimates of stresses in the system. Accordingly, the worst case stresses that could be induced in a system by HEMP will differ from the estimates obtained by extrapolating cw immersion test results. The difference between estimated and worst case HEMP stresses is sometimes referred to as the uncertainty associated with the estimate of HEMP-induced stress. This uncertainty should be taken into account when interpreting the results of cw immersion tests.

When approved by the verification test sponsor, shielding effectiveness measurements using procedures of MIL-STD-188-125 appendix A and a thorough SELDS survey in accordance with the guidance given in this handbook may be performed in lieu of the cw immersion test.

The cw immersion test is a tool to estimate HEMP-induced stresses (fields and cable currents) based on transfer function measurements acquired at low field strengths. These measurements are used for the following purposes:

a. To measure attenuation of electromagnetic fields in the HEMP portion of the spectrum by linear elements of the as-built electromagnetic barrier.

b. To identify HEMP shield and aperture POE protective device defects, faulty installation practices, and inadvertent POEs, so that repairs can be made.

c. To characterize residual internal field and conducted electromagnetic stresses, within limitations of the linearity and planarity assumptions, through posttest analysis.

d. To observe operation of the mission-essential equipment for interference or upset (interference which occurs as the result of the low-level cw excitation may indicate a circuit which is particularly vulnerable to HEMP effects).

e. To provide data for HEMP hardness assessment of the facility and baseline data for the hardness maintenance and hardness surveillance program.

Note that the fourth purpose listed above does not require special measurements, only observations of system functions. Low-level (approximately 1 V/m) cw fields can cause malfunctions in facilities; at least one case is known where cw immersion successfully jammed (admittedly unhardened) communication equipment at all frequencies.

Table XVIII summarizes the measurements required by MIL-STD-188-125, the corresponding requirement or pass/fail criterion to be met, and the applicable paragraphs in the standard.

16.3.3.3.1 Principles of cw immersion testing. A radiating antenna provides the swept or stepped frequency test excitation. In the stepped frequency case, the antenna radiates a low-amplitude, narrow-band sinusoidal field at several hundred discrete test frequencies between 100 kHz and 1 GHz. The measurement bandwidth (the frequency interval over which the system response is averaged) at any test frequency depends on the measurement time required to obtain a satisfactory signal-to-noise ratio. Typical cw immersion measurement bandwidths are on the order of 10 Hz. The spacing between test frequencies is much greater than the measurement bandwidth; hence, the system response transfer function is sampled relatively sparsely in frequency space.

Ideally, the number and spacing of test frequencies should be sufficient to resolve any resonances in the response of the system being tested. Fortunately, ground-based facilities are generally not highly resonant structures. Thus, facility responses can be expected to vary relatively slowly with frequency. For a system with a quality factor of 10, the response transfer function will vary only moderately over a 10 MHz interval at 100 MHz. Since quality factors as high as 30 are very rare, several tens of test points per decade of frequency will ordinarily be sufficient to resolve facility response transfer functions.

The threat environment can be horizontally polarized (E-field parallel to the ground), vertically polarized (E-field perpendicular to the ground), or any combination of horizontal and vertical polarization. Furthermore, the threat can be incident from any direction. Thus, a complete cw immersion test will include tests with horizontally and vertically polarized antennas, with several different transmitting antenna locations.

System responses to be measured inside the electromagnetic barrier include free-field measurements, surface current or charge density on the inner shield surface, and cable currents or voltages. The measurement points are chosen to provide a representative sample of the cw immersion responses in the protected volume. The measurements with a given transmitting antenna location should be concentrated in that part of the facility that is closest to barrier surfaces that are directly illuminated.

TABLE XVIII. MIL-STD-188-125 cw immersion measurements.

Measurement Type	Pass/Fail Criteria	MIL-STD-188-125 Paragraph Reference
BARRIER EFFECTIVENESS EVALUATION		
$\frac{B_{\text{intenal}}}{B_{\text{illuminating}}}$	$\leq$ *8000/w* for $w < 8 \times 10^8$; $\leq$10-5 for $w \geq 8 \times 10^8$	C.50.6.1.1
$\frac{E_{\text{internal}}}{E_{\text{illuminating}}}$	$\leq 10\text{-}^5$	C.50.6.1.2
$\frac{J\ s_{\text{internal}}}{B_{\text{illuminating}}}$	$\leq$ *6.4* x $10^9/w$ for $w < 8 \times 10^8$; $\leq$ 8 for $w \geq 8 \times 10^8$	C.50.6.1.3
$\frac{Q\ s_{\text{internal}}}{E_{\text{illuminating}}}$	$\leq 8.9 \times 10^{-17}$	C.50.6.1.4
Threat-extrapolated current	$\leq$0.1 A	C.50.6.2
NONINTERFERENCE WITH FACILITY OPERATIONS		
Functional monitoring of facility operation	No interference	C.50.6.3

Internal free-field measurements should be taken in areas that are relatively clear of equipment, and all three orthogonal components of the field should be recorded. Internal surface current or charge density measurements should principally be made at the penetration areas. When making surface current density measurements, the two orthogonal components of the response should be recorded.

The majority of cw immersion responses to be recorded will generally be currents on cables, cable shields, and cable bundles. To provide a representative sample from the literally hundreds or thousands of cables in a typical C^4I facility, the measurement point selection criteria should include the following:

a. Location with respect to the barrier and the MEE; measurement points should be chosen on selected penetrating conductors, close to the POE protective devices, and on selected cables where they interface to the MEE.

b. Location with respect to the floor plan; measurement points should be chosen in all areas inside the barrier.

c. Coupling geometry; cables with long interior runs and efficient coupling geometries should preferentially be selected.

MIL-STD-188-125 discusses the use of a rapid electromagnetic survey for locating areas of maximum response. The standard also defines the minimum number of measurements to be taken, which is a function of the facility size.

The diagram in figure 161 shows the cw immersion test and measurement setup for measuring an internal field and the current induced on a cable inside the shield. The external field is simultaneously measured by the reference sensor. The data acquired at this point are raw or uncorrected. Figure 162 shows the steps involved in processing the raw data to obtain the desired HEMP transient. This involves correction of the raw data for probe and signal processing calibrations, followed by extrapolation.

16.3.3.3.1.1 Data acquisition. The test and data acquisition is performed by the network analyzer, which in turn is usually controlled by a computer. The synthesizer in the network analyzer provides a low-amplitude sinusoid at a test frequency f to the power amplifier, which drives the simulation antenna. The antenna radiates a field (vertically polarized in the example shown) at the test frequency. This field induces a sinusoidal current I on the cable inside the HEMP shield. This current produces a proportional current probe output voltage V_T that is sent to the network analyzer via the test fiber optic link. The cw field also induces a voltage V_R in the reference field sensor. This voltage is transmitted to the network analyzer via the reference fiber optic link. At this

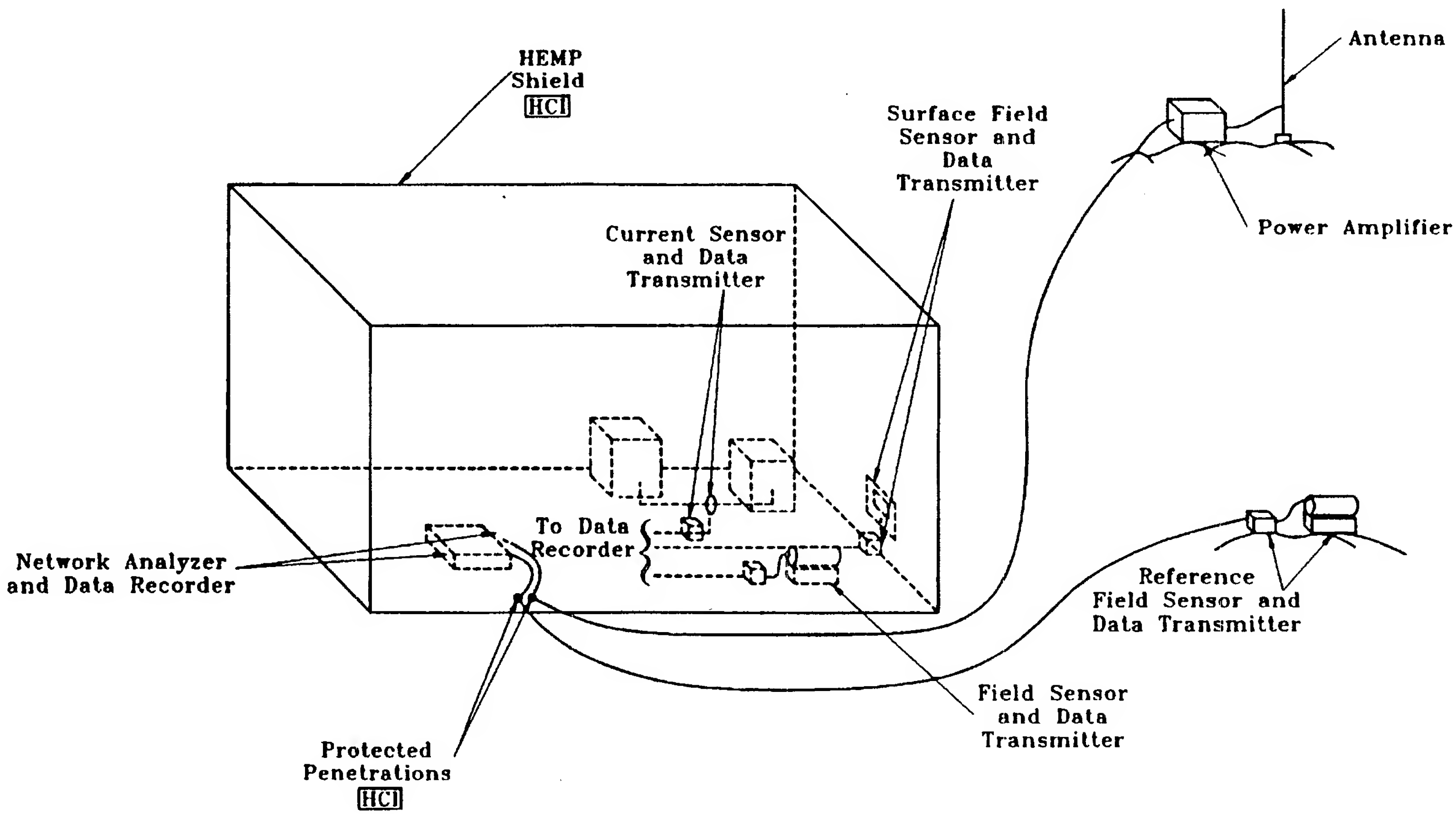


FIGURE 161. **Immersion test configuration (raw data).**

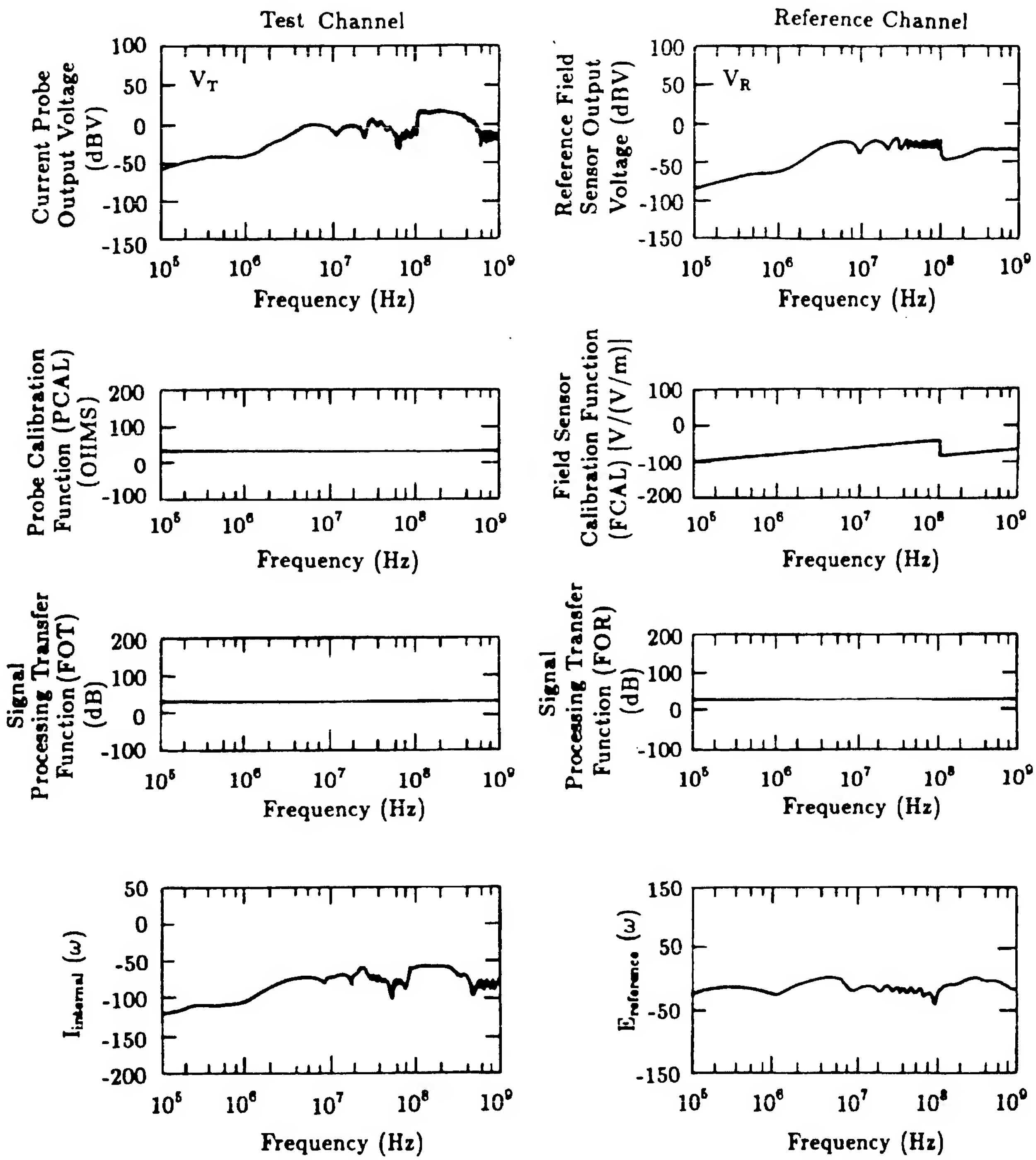


FIGURE 162. Processing required from raw data to final result (only magnitudes are shown).

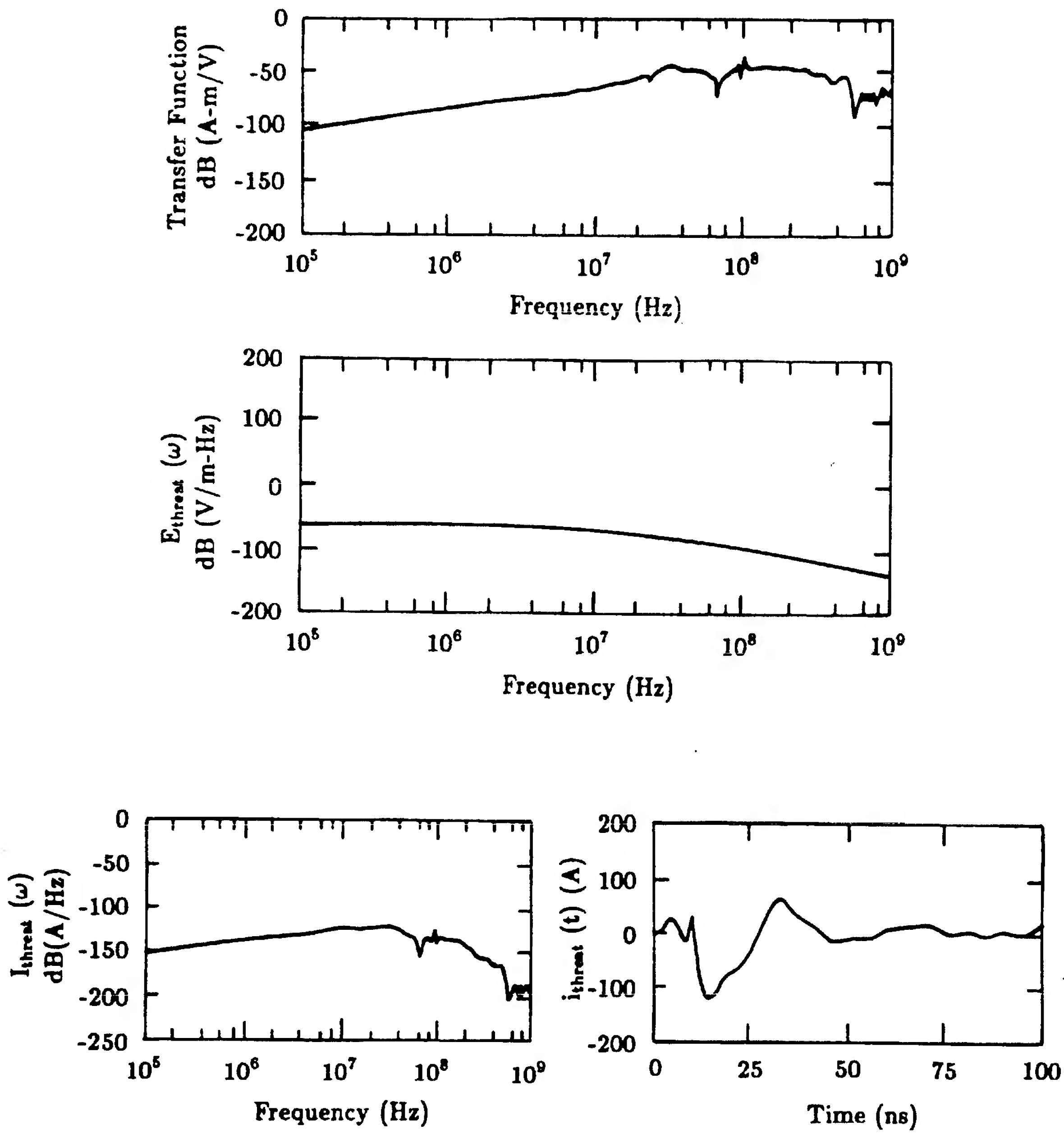


FIGURE 162. Processing required from raw data to final result (continued).

stage, the raw (or uncorrected) data acquired are the voltages in the test and reference channels, respectively. The frequency and the phase and amplitude values of V_T and V_R are recorded. Then this process is repeated at hundreds of frequencies between 100 kHz and 1 GHz.

Thus, the raw data consist of tables listing the test frequencies and the amplitudes and phases of the measured voltages V_T and V_R.

16.3.3.3.1.2 Data correction. The measured internal current response $I_{internal}$ and the measured reference field $E_{reference}$, are obtained from the raw data through the correction process.

$$I_{internal}(w) = \frac{V_T(w)}{FOT(w) \cdot PCAL(w)} \tag{17}$$

$$E_{reference}(w) = \frac{V_R(w)}{FOR(w) \cdot FCAL(w)} \tag{18}$$

where $w = 2\pi f$ is the angular frequency. $FOT(w)$ and $PCAL(w)$ are the frequency-dependent calibration functions for the signal processing devices and the current probe in the network analyzer test channel, respectively. $FOR(w)$ and $FCAL(w)$ are the calibration functions for signal processing devices and the field sensor in the reference channel. Signal processing devices may include an impedance matching network, preamplifier, fiber optic link, and other elements.

Additionally, it may be necessary to correct the reference field for facility reflections and location with respect to the transmitting antenna to obtain the principal component of the illuminating field. This operation is given by the equation

$$E_{illuminating}(w) = RRF(w) \cdot E_{reference}(w) \tag{19}$$

where RRF (W) is the referencing function. This referencing function can be determined experimentally or analytically.

16.3.3.3.1.3 Transfer function. The cw transfer function T is the ratio

$$T(w) = \frac{I_{internal}(w)}{E_{illuminating}(w)} \qquad \frac{\text{A-m}}{(\text{V})} \tag{20}$$

which is a complex (amplitude and phase) function of frequency. It is the current induced on the monitored cable by a 1 V/m principal component of the illuminating field as a function of frequency for the particular cw immersion test configuration.

16.3.3.3.1.4 Extrapolation. To obtain the test-based estimate of the HEMP-induced current on the monitored cable, the transfer function is scaled to the field that would exist at the facility in a HEMP event. MIL-STD-188-125 prescribes the equation to be used for this extrapolation as follows:

$$I_{threat}(w) = \frac{I_{internal}(w)}{E_{illuminating}(w)} \cdot E_{threat}(w) \tag{21}$$

where E_{threat} is the incident El HEMP threat spectrum specified in DoD-STD-2169 (reference 16-4).

The Fourier transform of the threat current spectrum is the time-domain threat response of the monitored cable. Because measured data is obtained over a limited range of frequencies in cw immersion testing, a Fourier transform cannot be performed over all frequencies. The test-based estimate of the time-domain threat response current for a swept frequency measurement is therefore calculated with the following equation:

$$i_{\text{threat}}(t) = \frac{1}{2\pi} \int_{2\pi f_l}^{2\pi f_u} \left[I_{\text{threat}}(\omega) e^{-i\omega t} + I^*_{\text{threat}}(\omega) e^{i\omega t} \right] d\omega \tag{22}$$

where

f_l = the lowest cw immersion test frequency (Hz)

f_u = the highest cw immersion test frequency (Hz)

$I^*_{threat}(w)$ = complex conjugate of $I_{threat}(w)$

For cw immersion with stepped frequency measurements, the integral becomes a summation as follows:

$$I_{\text{threat}}(t) \approx \sum_{n=1}^{N-1} \left[I_{\text{threat}}(\omega_n) e^{-i\omega_n t} + I^*_{\text{threat}}(\omega_n) e^{i\omega_n t} \right] \cdot \left[\frac{\omega_{n+1} - \omega_n}{2\pi} \right] \tag{23}$$

where N is the number of test frequencies and w_n is the *nth* angular test freuqency. The internal current pass/fail criterion is satisfied when the peak amplitude of $i_{threat}(t)$ does not exceed 0.1 A.

Note that the response in the passband of a typical low-pass filter will not be observed in a cw measurement with a lowest test frequency of 100 kHz. This explains the difference in residual current criteria between the cw immersion and PCI test procedures.

16.3.3.3.1.5 Signal-to-noise. To determine signal-to-noise properties of the cw immersion measurements, measurements of the ambient and pickup noise are required. The ambient noise measurement is acquired at the internal test point in the same manner as test data, except that the amplifier is muted (no fields radiated from the antenna). The pickup noise can be determined by varying the sensor cable routing and noting the effects on measured transfer functions.

The signal-to-noise properties of the measurement can be expressed in terms of the signal-t-noise ratio, but this ratio tends to vary rapidly as a function of frequency. Hence, it is more informative to plot both noise and signal as an overlay as suggested in MIL-STD-188-125. Figure 163 illustrates the signal-to-noise comparison for an internal electric field measurement. In the case shown, the signal and noise strength are approximately equal. Subsection 16.3.3 .3.2.3 addresses the situation when the measurement capability is limited by instrumentation and system-generated noise.

16.3.3.3.2 Practical cw immersion issues. While the principles of cw immersion testing are straightforward, their implementation at an actual test site requires the use of judgment and improvisation in response to site-specific conditions and constraints. Some of the major issues involved in implementing cw immersion testing are discussed in the following paragraphs. Further discussion and additional details can be found in references 16-5 and 16-6.

16.3.3.3.2.1 Simulation field characteristics. The early-time component of the incident HEMP field is specified as a uniform plane wave. However, the fields radiated by any practical antenna will only approximate a plane wave over the intended test volume. Moreover, the placement of the antenna with respect to the system or, equivalently, the location of the system with respect to the working volume of the antenna, may be constrained. Thus, implementation of cw immersion testing requires identification of the effective working volume of the antenna that will be used, selection of the location of the antennas with respect to the system, and estimation of the impact of non-planarity of the fields on test results.

The simulation fidelity depends on the specific antenna used. The antenna should be characterized in a field mapping prior to cw immersion tests to determine its working volume, i.e., the volume over which the fields are an acceptable approximation to a plane wave with quantifiable deficiencies. For planning purposes, the working volume of an antenna should be taken as that volume throughout which the major incident field components, without ground reflection, do not deviate in intensity by more than a factor of two (6 dB) from the value at the center of the test volume.

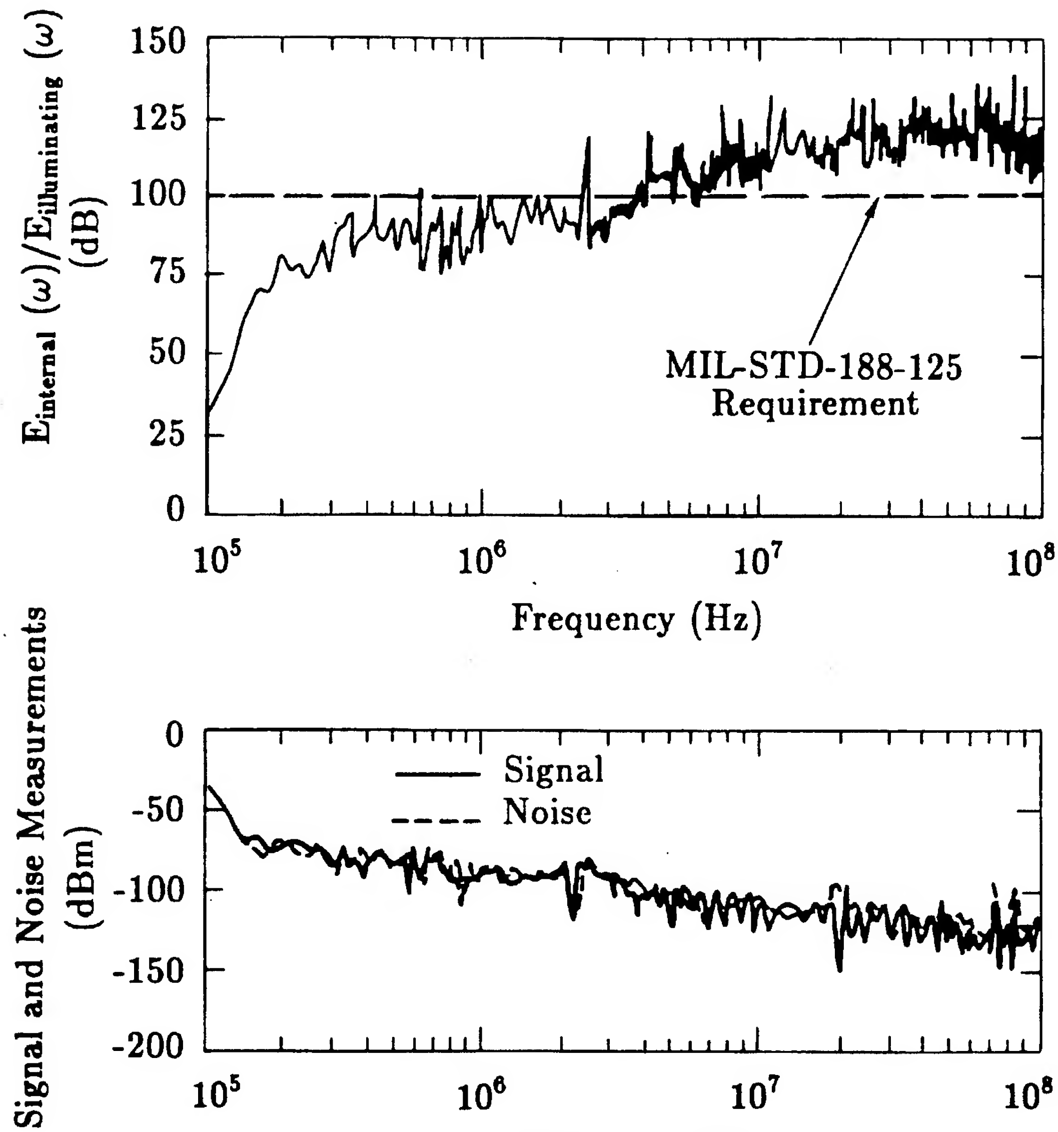


FIGURE 163. Electric field measurements and the MIL-STD-188-125 pass/fail criterion.

Ideally, the antenna should be placed at the site such that the facility under test is wholly within its working volume. However, the placement must be compatible with the physical constraints (buildings, roads, railways, etc.) at the test site. In the event that the facility under test extends beyond the working volume, the maximum variation of the major field components across the test object should be determined.

The following general rule, illustrated in figure 164, can be used to choose transmitting antenna locations. The largest dimension of the barrier area considered to be adequately illuminated from a particular transmitting antenna location should be less than or equal to the distance from the antenna to the closest point on the shield. Thus, as seen in figure 164, only half of the barrier surface is satisfactorily illuminated from position #1. Conversely, the entire surface is illuminated properly from antenna position #2. If the application of this rule and the facility size and physical constraints on antenna placement lead to an excessive number of transmitting antenna positions, shielding effectiveness measurements should be substituted for cw immersion in the verification test program.

16.3.3.3.2.2 Reference sensor. The HEMP-induced stresses are estimated on the basis of simulating (in part experimentally and in part numerically) threat-level HEMP fields at the facility. Therefore, the type and location of the reference sensor are crucial for successful cw immersion tests.

a. The reference sensor must be oriented along a major field component, i.e., a component of the plane wave to be simulated. For example, the vertical electric field for vertically polarized cw immersion tests.

b. The reference sensor must measure a strong net (incident plus ground-reflected) field component. For instance, in a horizontally polarized cw immersion test, the horizontal electric field component parallel to the antenna axis is a major incident field component, but the net field is weak near the conducting ground. Therefore, the horizontal component of the radial magnetic field is a better choice as a reference.

The component to be measured must be a vertical electric field or horizontal magnetic field, because the ground reflections of these components are in phase with the incident fields. The direction of the horizontal magnetic field component should be azimuthal for a vertical monopole or radial for a horizontal dipole. The location must be one with a known relationship to the illuminating field.

16.3.3.3.2.3 Sensitivity/dynamic range. The lowest signal detectable by the data acquisition system determines the sensitivity. The dynamic range must be sufficiently large to make comparisons with the MIL-STD-188-125 pass/fail criteria possible. For example,

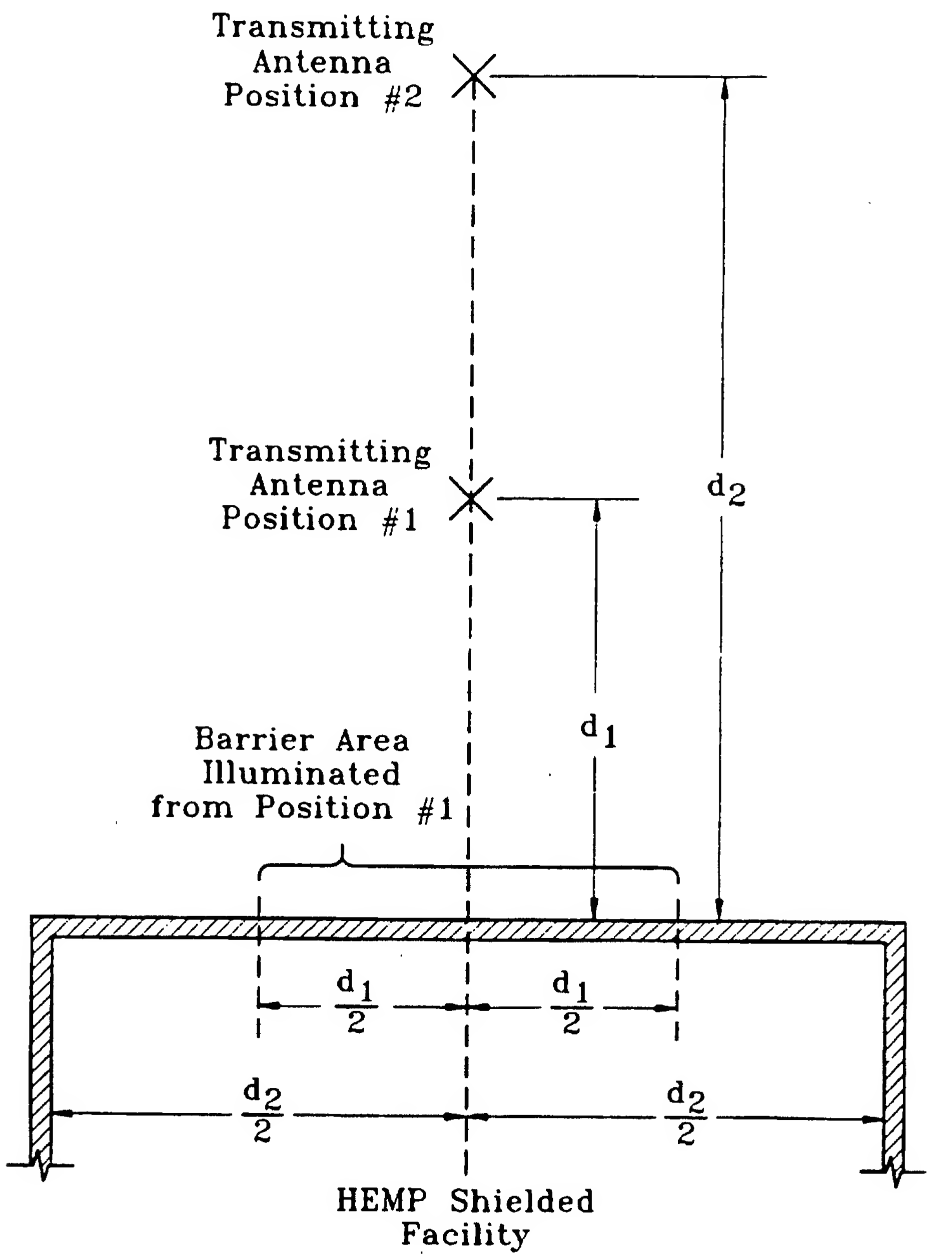


FIGURE 164. Transmitting antenna position selection.

to demonstrate that the electric field inside the shield is at least 100 dB below the external field, a dynamic range of at least 100 dB is necessary.

The signal-to-noise and dynamic range requirements for cw immersion measurements are addressed in MIL-STD-188-125 by setting minimum objectives for the data acquisition system sensitivity and radiated field strength. The data system should be capable of recording a sensor output signal at –147 dBm. The principal component of the illuminating field should be at least 0.1 V/m from 100 kHz to 1 MHz, at least 1 V/m from 1 MHz to 50 MHz, at least 0.1 V/m from 50 MHz to 100 MHz, and at least 0.01 V/m from 100 MHz to 1 GHz. These goals are achievable over most of the cw immersion spectrum with available instrumentation and antennas.

When the sensitivity and field strength objectives are met, the test system has sufficient dynamic range for making pass/fail determinations. If the system-generated noise limits the minimum detectable signal level, however, the range of measurements may no longer be adequate for this purpose. When this situation occurs with an internal field measurement, the shield attenuation is considered to be satisfactory when there is no observable response above the noise level. Processing of noise-limited cable current measurements is discussed below.

The following points should be considered when selecting the equipment to perform cw immersion testing:

a. The measurement dynamic range improves with increasing antenna radiation efficiency, amplifier power, and decreasing detection bandwidth. However, there are practical constraints on each item: the radiation efficiency is inherent in the antenna design and cannot be modified at will; the amplifier power is limited by the site frequency management and by available amplifiers (typically 1 kW up to 100 MHz and 40 W above 100 MHz); and the smallest practical detection band width is 1 Hz.

b. The minimum detectable signal may be limited by either ambient noise at the test point or by the data acquisition system sensitivity. Test equipment available today meets the dynamic range requirements of MIL-STD-188-125 in the absence of ambient noise.

c. Sensitivity also depends on the measurement type (field or current measurement) and the probe characteristics. From equation 17, it follows that the probe transfer impedance (PCAL) affects the lowest detectable signal. In other words, the sensitivity using a 5-Ω current probe is five times better than that using a 1-Ω probe. For field measurements, derivative sensors are usually employed. These sensors have a calibration curve which varies as wA, where w is the angular frequency and A is

the sensor effective area. Hence, the sensitivity of field measurements is directly proportional to frequency.

d. If the ambient noise dominates a measured current signal, then equation 20 provides an upper bound on the transfer function, and equation 21 provides an upper bound on the stress spectrum. When the amplitude of a stress measurement is largely noise, the phase is largely noise as well. Because of the resulting lack of phase information, it may not be possible to perform the inverse Fourier transformation (equation 22 or 23) to determine the time domain stress transient as required in MIL-STD-188-125. In this case, the following inequalities can be used to provide an upper bound on the peak value of the unknown transient:

$$|i_{\text{threat}}(t)| \leq \frac{1}{\pi} \int_{2\pi f_l}^{2\pi f_u} |I_{\text{threat}}(\omega)| \, d\omega \tag{24}$$

$$|i_{\text{threat}}(t)| \leq \sum_{n=1}^{N-1} |I_{\text{threat}}(\omega_n)| \cdot \frac{\omega_{n+1} - \omega_n}{\pi} \tag{25}$$

16.3.3.3.2.4 Frequency management. The test frequencies and radiated power levels must be coordinated in advance with the local frequency management authority, who identifies frequencies or bands that may not be used for testing.

Data on the bandwidth characteristics of the radiated cw immersion signals should be provided to the local manager in the request for frequency clearance. With this information, any tendency to unnecessarily restrict emanations over large segments of the electromagnetic spectrum can be avoided. Relatively narrow exclusion bands to prevent interference at the specific frequencies and bandwidths used for area communications and other activities can be precisely identified.

16.3.3.3.3 Uncertainties. The test-based internal stress estimates obtained from cw immersion are subject to several uncertainties. These uncertainties have been taken into account in the MIL-STD-188-125 data analysis equations and pass/fail criteria for this test. However, the effects of uncertainties must be considered when cw immersion is used to obtain coupling measurements for verification testing on special protective measurements (see 16.3.3.6).

16.3.3.4 Shielding effectiveness verification testing. While cw immersion is the preferred radiated field verification test method, MIL-STD-188-125 permits the use of shielding effectiveness and SELDS measurements for this purpose when approved by the sponsoring agency.

When the substitution is authorized, shielding effectiveness tests are performed in accordance with procedures in appendix A of MIL-STD-188-125. Additional guidance provided by 16.3.2.4 of this handbook also applies, except that the facility must be in a normal operating configuration and the MEE must be performing actual or simulated mission functions. Pass/fail criteria are as specified by the curve of minimum shielding effectiveness versus frequency.

The accompanying SELDS survey should be performed as described in subsection 16.3.1.8.

The advantage of cw immersion is that fields and currents measured inside the protected volume can be related (with uncertainties) to the threat. The acquired verification data therefore supports quantitative characterization of the interior electromagnetic environment, as well as identification of barrier defects.

The shielding effectiveness/SELDS test method is equally effective as an indicator of barrier electromagnetic leakage and is superior to cw immersion in fault localization, but measured results cannot be correlated to residual internal threat stresses. Since the radiative excitation is generated by small antennas close to the surface under test, physical or electromagnetic interference with other facilities in the vicinity is minimized. Testing costs for shielding effectiveness/SELDS measurements are comparable to those for cw immersion.

It is recommended that the shielding effectiveness/SELDS method be used as the shielding effectiveness verification test procedure when any of the following conditions exist:

a. Other structures in the area near the shield under test preclude selection of favorable cw immersion transmitting antenna locations.

b. The size of the facility and physical constraints on transmitting antenna position placement leads to an excessive number of illumination positions.

c. Electromagnetic spectrum management considerations significantly restrict the magnitude or frequency coverage of radiated emissions, such that dynamic range objectives for cw immersion measurements cannot be satisfied.

16.3.3.5 Pulsed current injection verification testing. There are major differences between PCI verification testing and PCI acceptance testing. In PCI acceptance testing, only the performance of POE protective devices is evaluated. The verification procedure

also evaluates the operation of mission-essential equipment in the presence of the residual internal electromagnetic stresses and assesses the effects of these stresses on mission capabilities.

The most significant differences are:

a. Test configuration – mission-essential equipment is connected to the circuit under test during verification.

b. Power – PCI verification testing is done with normal power applied to the circuit under test.

c. Test requirements – common mode PC I tests are required for verification on power lines, audio/data lines, and control/signal lines; wire-to-ground PCI tests are not required on audio/data lines; furthermore, multiple tests of a circuit are required.

d. Pass/fail criteria – success in a PCI verification test requires that there be no damage to or upset of mission-essential equipment, that there be no interruption of mission-essential functions, and that POE protective treatments comply with all performance requirements.

PCI acceptance testing is described in 16.3.2.4; only differences between acceptance and verification testing are addressed in succeeding subsections.

16.3.3.5.1 Principles. MIL-STD-188-125 does not specify minimum electromagnetic susceptibility thresholds for communications-electronics equipment which will be installed and operating within the protected volume. Therefore, even though the stress control specifications for POE protection treatments are stringent, they do not guarantee that residual internal stresses will not damage or upset mission-essential equipment. The PCI verification test is intended to determine whether the POE protection is sufficient or whether special protective measures will be required in order to achieve hardness.

PCI procedural differences outlined in this subsection support this additional test objective. Instead of disconnecting the mission-essential equipment, it remains in the circuit under test. Furthermore, the equipment is to be powered (except when safety considerations dictate otherwise) and functioning in its mission capacity when the test excitations are applied.

Another major difference is the need for multiple pulses for an adequate evaluation of the functional response. Two to six pulses should typically be performed at the injection level which produces the largest residual internal transient stress. The specific number of

pulses on a particular circuit should be specified based on results of the state analysis (see 16.3.3.5.2). When the penetrating conductor interfaces to a simple circuit, such as a relay contact, two pulses in each state may be sufficient. As the complexity of the attached MEE increases, a larger number of excitations should be applied. For very complex equipment, such as a digital system with many uncontrolled state transitions, more than six pulses may be necessary to perform the functional response evaluation. In all cases, a monitoring approach capable of detecting upsets and damage must be implemented.

As in the acceptance procedure, reasonable worst case transients are injected for PCI verification, and protective device performance is quantified. Additionally, however, equipment and mission operations must be monitored by trained personnel to detect any abnormal occurrences.

16.3.3.5.2 Operating state analysis. When internal equipment which is connected to an electrical POE has multiple operating states and when the distribution of stresses to MEE inside the barrier or the functional response of MEE depends on the operating state of the equipment, then testing should be performed in each state. The term 'operating state," as used here, refers to either the manner of connection of equipment inside the HEMP barrier to a POE or the manner in which the equipment is used. For example, consider a transceiver connected to an rf antenna line penetration. In the transmit mode, the residual transient is applied to the transmitter output stage. In the receive mode, the residual transient is applied to the receiver bandpass filter and detector. Since entirely different components are stressed depending on the position of the transmit/receive switch, the circuit should be tested in both states.

Another example would be the connection of a power line leading out from a facility through a POE in the HEMP barrier to an external load. The internal equipment states might be breaker open (power off) and breaker shut (power on). It can usually be said in this case that the power-on condition is the more vulnerable state, and only this condition must be tested.

The verification test planner must become thoroughly familiar with the operation of the mission-essential equipment in order to perform the pretest operating state analysis. Operational states of all internal equipments interfacing with electrical POEs must be identified and assessed, and configurations in which tests are to be performed must be determined. The planner for this task should employ the assistance of knowledgeable personnel, including experienced operators and the system developer. Usually, the analysis can be performed by tracing and constructing schematic diagrams of the first few interface levels beyond the point of switching. If a determination cannot be made on the basis of these drawings, then a detailed circuit transient analysis should be performed.

The state analysis task relies heavily on the engineering judgement of the analyst. When it is apparent that the MEE is not vulnerable in a particular state, then it is not necessary to test the system in that state. Only one firm rule can be provided. If it is uncertain whether a circuit should be tested in a particular state, then it should be tested.

16.3.3.5.3 Test equipment. With two exceptions, excitation source and instrumentation requirements for PCI verification testing are the same as those for the PCI acceptance test. Only the differences will be addressed here, and the reader should consult 16.3.2.4.4 for information on the features common to acceptance and verification.

The pulse output coupler serves several verification test functions, as shown by figure 165. The schematic diagram illustrates a common-mode PCI test on a 3-phase power line feeder to an external load. The pulse is assumed to be directly coupled into the lines under test, although other coupling techniques exist. The verification test functions of the coupler are:

a. To couple the injected waveform from the pulse generator, through the injection path elements, to the POE protective device under test.

b. To protect the pulse generator from line voltages and currents by the blocking action of the injection path elements.

c. To block transmission of the pulse in the direction toward the external load by action of the line elements. (This protects the external equipment from the injected transient and prevents undesirable current division at the injection point.)

d. To pass circuit operating signals through the line elements without significant loss or distortion.

e. To prevent phase-t-phase and phase-to-neutral short-circuits.

For the short duration PCI pulse, metal oxide varistors are commonly used as the injection path elements. The line elements for the short pulse will usually be series inductors. Other techniques may be required for the intermediate, long, and damped sinusoidal pulses, and some of these couplers are still under development. Since the operating signals are not present and the external equipment is not connected during acceptance testing, only the first of these five functions applies to that test.

Secondly, current sensors must be capable of sensing the transient signals in the presence of normal operating currents. The problem is particularly difficult when measuring internal responses to short pulse excitations, when the residual transients may be orders

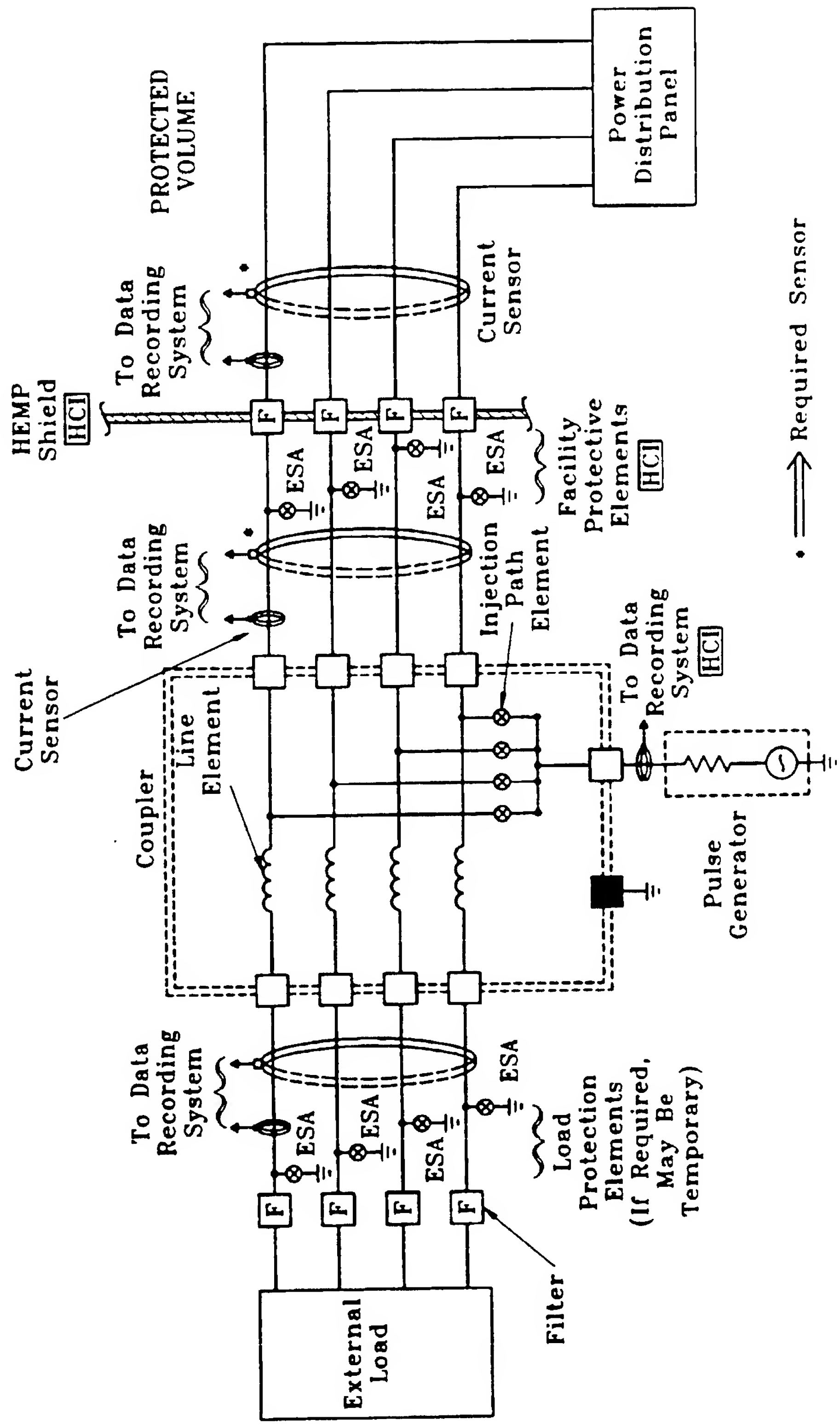


FIGURE 165. Power line common mode injection test.

of magnitude smaller than the line currents.[9] Saturation characteristics can become an important factor in the probe selection. Also, the sensor aperture size must accommodate multiple conductors for bulk current measurements (or multiple measurements must be made and then summed).

16.3.3.5.4 Test planning and execution. Pretest planning and PCI verification test performance involve all of the features identified in connection with PCI acceptance testing (see 16.3.2.4.5). For example, as in acceptance testing, PCI verification testing will require a series of current injections at increasing amplitudes. However, during verification some new elements must be present. Each of these elements increases somewhat the demands on the test planner and imposes additional test performance requirements.

The facility being tested often must perform its mission continuously during verification. This requires that spare filters and surge arresters (see section 17) must be available on site to permit immediate repairs, in the event that a device is damaged by the high-level testing. Furthermore, before removing a circuit from service, alternate equipment must be brought on-line to perform the affected function or functions. This may be as simple as switching between installed on-line and standby subsystems; other cases have involved rerouting critical defense traffic to a different C^4I installation. Identification of needed "work-arounds" in pretest planning and thorough preparation for such transitions can avoid costly delays during the on-site experimental program.

System downtime, if permitted, will normally be brief. Downtime must be arranged well in advance, and the test team must be fully prepared to promptly execute and complete applicable sequences before the scheduled return to operational status.

A requirement also exists for monitoring MEE operations during verification pulse tests. Potential upset and damage modes associated with each circuit to be tested should be identified. The planner then determines the observable to be monitored for the purpose of detecting these occurrences and uses built-in system diagnostics or trained operators to perform the monitoring. Instructions for recording functional information should be included in detailed test procedures as explicitly as possible.

During the verification testing, it is important that the system be performing the kind of functions that it will perform during its service life, and that it be possible to detect any malfunctions. Although MIL-STD-188-125 requires that the system be operating during the verification test, and a criterion for acceptance is that the "residual internal transient stresses will not cause mission-aborting damage or upsets of the MEE in its

[9]MIL-STD-188-125 specifies alternate measurements to be made when responses cannot be discriminated from circuit operating and noise signals.

various operating states," the procedure for ascertaining acceptability is not prescribed. In fact, the mission and the acceptability criteria vary widely, so that these rules must be defined for each facility or class of facilities.

If the MEE is not processing operational data or communications during the verification test, this function should be simulated with a system that supplies a data stream to the receiving ports of the system and monitors the data stream delivered through the output ports (antennas, cables, and fiber optic lines). In developing the simulation programs, the goal is to exercise all operating programs used to process critical, time-urgent messages and exercise all hardware used to process or support the processing of critical, time-urgent messages.

Past tests of digital systems have demonstrated that a system response to a simulated HEMP pulse is often delayed, because the affected function is used only periodically or because of the time it takes for the error to propagate through the digital system. Thus, it is important that all software-whether stored in random-access memory or read-only memory; on disks, plated wire, or other storage media—be exercised during verification tests. The system must be checked, after the tests to ascertain that the operating instructions or data have not been altered by the test pulses. Such posttest examinations must be especially thorough if test-induced upsets in the operation of MEE are to be detected. Also because of the delay, the system response to a test pulse may not occur until minutes or hours after the stimulus.

In order to ensure that malfunctions observed during testing can be distinguished from ordinary (without HEMP testing) malfunctions and to ensure that the likelihood of malfunction can be accurately established, the following conditions should be met:

a. The verification test time should be short compared to the mean time between failure of the system being tested.

b. The time between individual verification test excitations that are used to establish likelihood of malfunction per exposure should be longer than the malfunction response time.

For complex, digital electronic systems it is generally not possible to determine malfunction response times on an a priori basis. Hence, it is permissible to begin testing using multiple excitations spaced closely in time for the purpose of establishing that no malfunctions can be expected. However, if a malfunction is observed during testing, the excitation repetition rate should then be decreased sufficiently to allow correlation of malfunctions with individual pulses. For this purpose, individual excitations should be separated by the

total elapsed time it took any malfunction to be observed at higher repetition rates, plus the time necessary to establish the likelihood of malfunction per excitation.

Most of the hardware used to process or support the processing of critical, time-urgent messages will be exercised if all of the operating programs are exercised. Thus, all communications-dectronics equipment and supporting equipment, such as air conditioning, uninterruptible power systems, and standby generators should be monitored. Equipment in special protective volumes should be carefully monitored during the verification test and thoroughly checked after the test. Particularly in these volumes, there should be a concern for overstresses that may damage or degrade components. Since the effects of overstress may not be immediately evident (e.g. the life may be shortened, but this is not obvious immediately after the test), it may be necessary to carefully monitor the HEMP-induced stress and compare it to the manufacturer's specifications.

The development of system check-out test procedures, for use during and after the verification test, is strongly recommended. The use of internal monitoring functions, rather than normal status displays, to diagnose the cause and origin of malfunctions is desirable, since upsets do not always affect the observable system displays. In addition, it is desirable to develop posttest diagnostic procedures to detect possible effects of overstress such as increased leakage in MOVs and filters, weakened insulation in capacitors and other high stress areas, or degraded semiconductor characteristics.

Additional personnel and equipment safety issues arise because PCI verification tests are conducted on energized circuits with operational hardware connected. Verification test requirements for pulse output couplers have already been mentioned. Vulnerability estimates must be made on external loads to determine whether isolation provided by the coupler is adequate or if supplemental protection is required. Extreme care must be exercised to avoid inadvertently grounding live circuits with the instrumentation cabling.

Finally, in some instances, operational signals on the conductor under test will be superimposed on the residual transient waveform and will prevent accurate computation of response norms. In these cases, the PCI verification test is first performed on the energized circuit to make the functional pass/fail determination. Injections are then repeated in the deenergized acceptance test configuration to verify acceptable protective device performance.

16.3.3.5.5 Data recording, format, and disposition. PCI verification data should be handled in the same manner as PCI acceptance test records (see 16.3.2.4.6).

The verification-unique aspect of PCI data recording is the test chronology. This will normally be in the form of a narrative logbook written by the tester to record the sequence of test events and to highlight all unusual occurrences.

Test-induced damage or upset can sometimes take place well after the simulated excitation has passed. Therefore, a determination whether the occurrence was caused by testing or was unrelated to the PCI transients cannot necessarily be made in real time. To facilitate posttest analysis, a careful record of all abnormal observations must be made. Information to be preserved includes nature of the occurrence, system conditions at the time of the problem, readings from relevant system indicators before and after the event, and time of the occurrence relative to milestones in the test sequence. A thorough description of the investigation of the problem and any corrective actions taken should also be provided. Failed components should be saved for later examination.

16.3.3.6 Verification of special protective measures.

16.3.3.6.1 Hardening using special protective measures. Special protective measures are to be employed when:

a. MEE is not enclosed within an electromagnetic barrier.

b. MEE is enclosed within an electromagnetic barrier but it experiences mission-aborting damage or upset during verification testing, even though the barrier elements satisfy all performance requirements.

c. POE protective devices cannot satisfy the barrier requirements without interfering with facility operation.

Because the SPMs are an essential part of the HEMP hardening of the facility, their effectiveness must also be verified.

16.3.3.6.2 Overview of verification for SPMs. The concept for hardness verification of SPMs used to protect mission-essential equipment is a three-step process. First, measurements are made to quantify the transfer functions between the field environment and coupled currents on the equipment conductors. These measured current responses are then extrapolated to determine the reasonable worst case transients that could be induced by the DoD-STD-2169 threat. Finally, the MEE is tested by pulsed current injection to demonstrate that the the HEMP-induced current stresses are at least 20 dB less than the conducted transient vulnerability thresholds of the equipment.

The implementation of this concept is not always straightforward, due to the great variety of possible SPMs. For example, equipment in the category of MEE outside the barrier ranges from a small electromechanical sensor or motor to antennas. MEE in a special protective volume is typically a radio transmitter or transceiver. Unusually sensitive equipment in the protected volume may be of almost any type. Therefore, the specifications for verification testing of equipment hardened with SPMs cannot be described by simple generic rules.

Verification for SPMs requires special tests, which are tailored and applicable to the specific SPM to be verified. This subsection discusses some options for implementing the MIL-STD-188-125 verification requirement for some SPM types encountered in practice. Both coupling measurements and pulsed current injection tests are required. The coupling measurement techniques will be discussed first. Pulsed current injection verification for the three MEE categories will then be discussed separately.

16.3.3.6.3 Coupling measurements. Threat-level illumination testing, threat-level skin current injection, and cw immersion are the three types of coupling measurements explicitly identified in MIL-STD-188-125. Threat-level illumination can be performed by taking the equipment to a simulator or constructing a simulator at the facility under test. Skin current injection can be performed using the PCI simulators. A discussion of cw immersion is presented earlier in this section.

Any of these methods or any other threat-relatable test may be used to obtain coupling measurements on MEE outside the electromagnetic barrier; the choice is left to the verification test organization. Regardless of the method selected, the test-based estimates of the coupled stress must be adjusted to account for uncertainties. This adjustment must be made before the factor of 10 is applied to determine the PCI drive levels. Subsection 16.3.3.6.4 addresses uncertainties.

For MEE in a special protective volume, the coupling measurements can be obtained during the PCI test of the filter/ESA assembly leading into the SPV. Each of the cables in the special protective volume should be monitored. The largest signal observed during the sequence of drive levels is considered to be the reasonable worst case threat response for that cable.

Separate coupling tests for unusually sensitive MEE in the protected volume are not required if the maximum allowable residual internal stress on each cable connecting to that equipment is used as the reasonable worst case threat response. Alternatively, signals measured on these cables during the PCI verification test can be used for this purpose.

16.3.3.6.4 Coupling measurement uncertainties. Estimates of the coupled stress determined by all types of coupling tests, from high-level threat-like simulators to cw immersion, will differ from the reasonable worst case HEMP-induced responses for numerous reasons. Some of these differences or uncertainties are associated with the test equipment. Other sources include nonlinearities and errors in measurement or extrapolation. The test-based estimates must be adjusted to account for these uncertainties before the factor of 10 is applied to determine the PCI drive levels.

Examples of uncertainties associated with the test equipment and system configuration include the following:

a. Uncertainties due to amplitude, waveform, and wave impedance deficiencies in threat-like illumination simulators.

b. Uncertainties due to variations in the angles of polarization and incidence. The values of these parameters in the coupling test may not be reasonable worst case. Furthermore, one cable in a system may couple most efficiently to a horizontal electric field, while another may respond best to a vertical electric field.

c. Uncertainties due to variations in the test article configuration, including all intentional and inadvertent connections between the equipment under test and other potential collectors of HEMP energy.

d. Uncertainties due to variations in the soil conductivity. Changes in site soil conductivity occur due to the weather and the season.

A typical approach for addressing this group of uncertainties is to develop an analytical or numerical model of the system under test. Using the measured results, the model is refined until it accurately predicts responses to the test excitation. Parameter variation studies are then performed with the DoD-STD-2169 threat environment to determine the reasonable worst case HEMP transient for each conductor.

Nonlinear system responses occur because HEMP-induced voltages may become sufficiently high to activate electronic surge arresters, cause corona, and initiate unintentional arcs. These effects will not be observed in low-level tests such as cw immersion. The impacts of nonlinearities can be estimated by comparing extrapolated low-level measurements or predictions with high-level pulsed data. Another approach is to simulate nonlinearities in low-level experiments by placing low-impedance shunts at the likely breakdown locations.

Uncertainty is inherent in measurements; error bounds can be established by making a statistically significant number of independent repeatability measurements of each type. Similarly, all analytical processing of data requires assumptions and approximations that introduce uncertainties. The analyst should attempt to estimate the error bounds associated with each processing operation.

It is suggested that the square root of the sum of the squares of the maximum uncertainty of each type be used to determine the combined uncertainty. In the absence of better information, a combined uncertainty not less than 20 dB is recommended. This combined uncertainty should be applied to the test-based coupling estimate to determine the predicted HEMP stress. The resulting amplitude is multiplied by 10 to determine the maximum PCI drive amplitude.

16.3.3.6.5 Verification of MEE outside the HEMP barrier. All MEE that will operate satisfactorily within a HEMP barrier must be placed inside the barrier. Examples of MEE that may be placed outside the barrier include antennas and heat exchangers.

Verification test requirements for MEE outside the barrier will be illustrated with an example from an existing satellite communications earth terminal complex. Although the facility was constructed before MIL-STD-188-125 was issued, the HEMP protection subsystem is very similar to that required by the standard. The barrier consists of a 100 dB (nominal) shield and POE protective devices on penetrations. Two exceptions to the standard can be seen in figure 166. The telephone and digital data lines enter the protected volume through filter/ESA protective devices, rather than being converted to fiber optics. Furthermore, single rf doors are installed at two locations.

The equipment heat exchangers are MEE outside the barrier and are hardened with special protective measures. Figure 167 shows the SPMs recommended in section 14 for such installations. The actual hardening provided at the earth terminal complex is very similar to this recommended approach.

The verification test methodology for this SPM installation is illustrated in figure 168. It must include coupling measurements as described in 16.3.3.6.3 and PCI tests. Coupling measurements should be made at the following locations:

a. On the system of shielded conduits and enclosures (including the shielded compartment of the filter/ESA assembly on the motor leads); three measurement points on this system are shown in figure 167.

b. On all conductors within the flexible conduit from the filter/ESA assembly to the motor connection box.

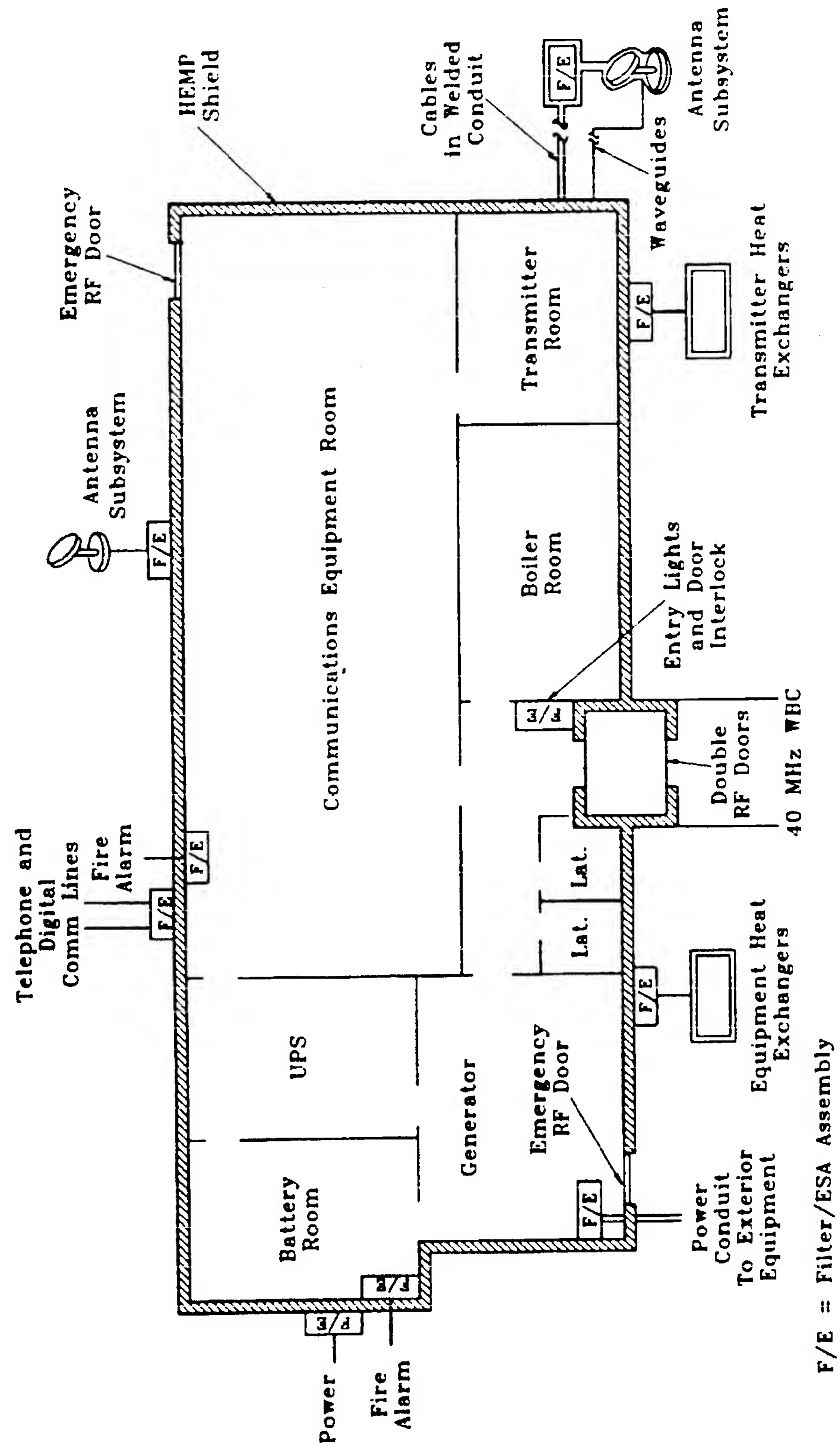


FIGURE 166. **Earth terminal complex.**

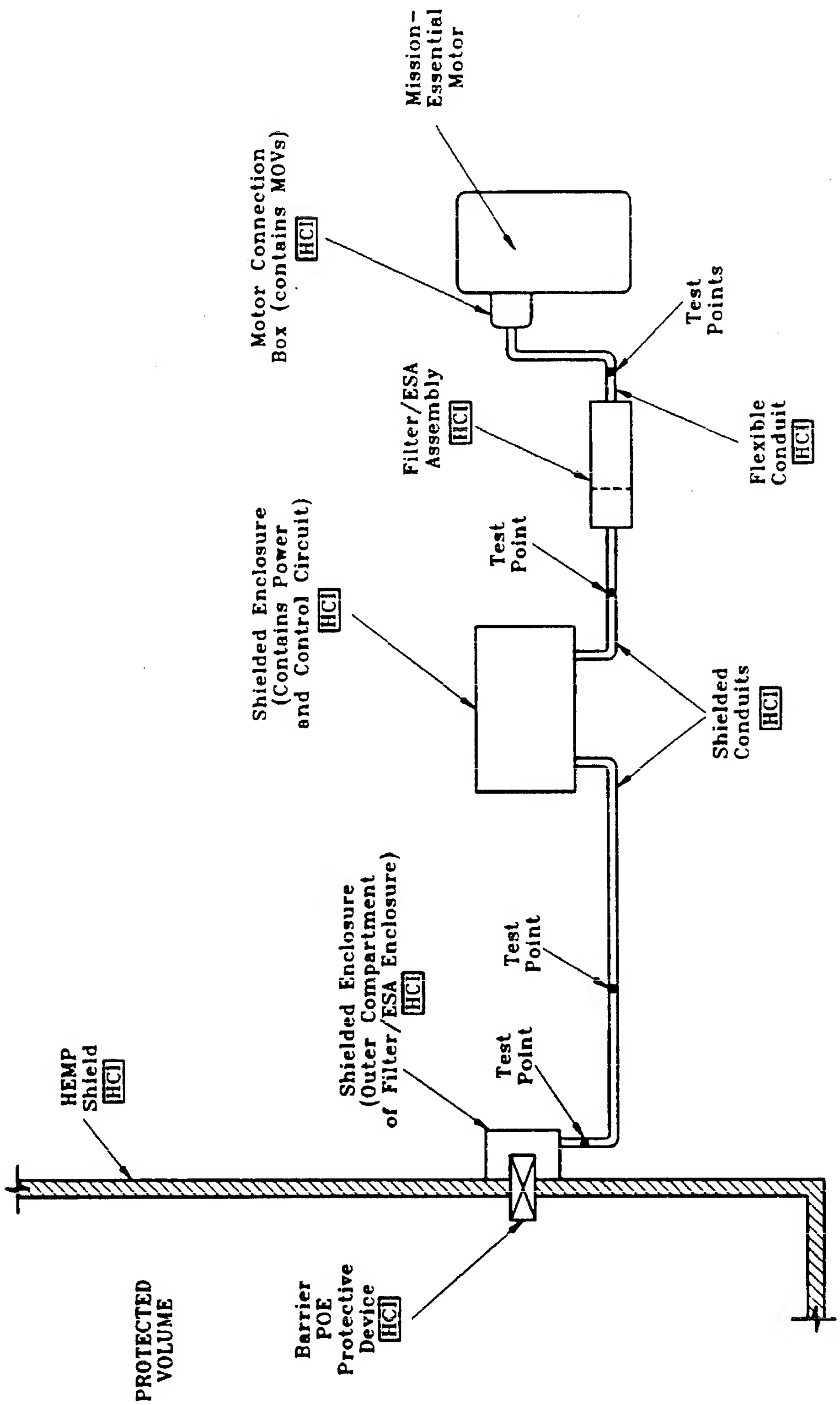


FIGURE 167. Mission-essential motor protected with special protective measures.

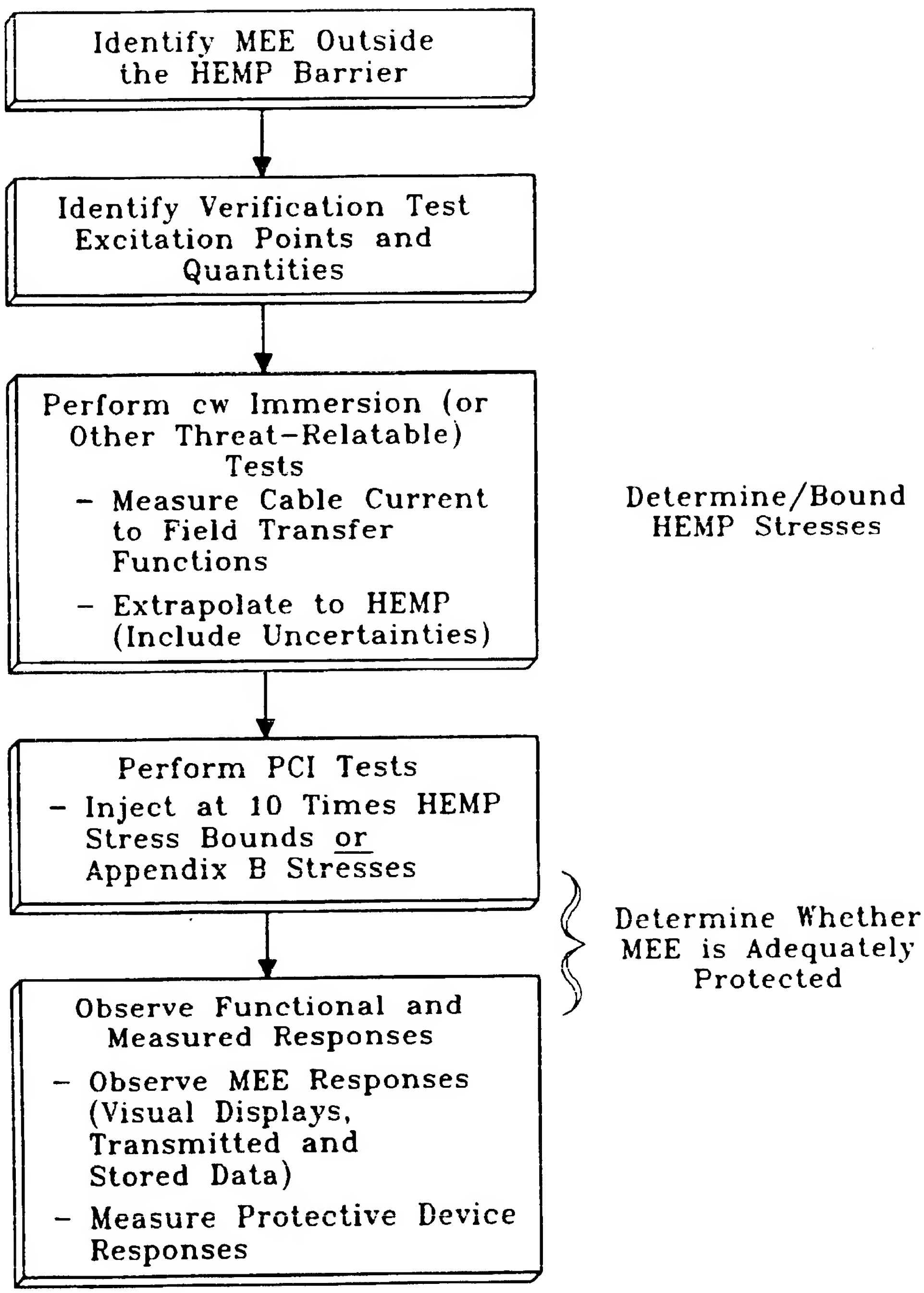


FIGURE 168. Verification for MEE located outside the electromagnetic barrier.

These measurements can be made using cw immersion testing. The test-based estimates must be adjusted to account for the uncertainties, then multiplied by 10 to determine the maximum PCI drive levels.

The PCI excitations should be implemented such that the peak rate of rise norm and the action integral norm, as well as the peak amplitude norm, are at least 10 times the reasonable worst case stress values of these parameters at the maximum excitation. The PCI test at each drive point begins at a level below that required to trigger the nonlinear devices. If the results are satisfactory at the first level, the drive amplitude is increased by a factor of approximately two. This series is continued until the drive point has been pulsed at the required maximum level.

One PCI sequence is performed on the shielded conduit/enclosure system. PCI tests are also required on each of the conductors within the flexible conduit to demonstrate that the filter/ESA assembly provides adequate transient suppression/attenuation and to verify that the motor vulnerability threshold is at least 20 dB greater than the reasonable worst case HEMP stress. The heat exchanger must be operating during these tests, and its functional performance must be monitored. Any system upset or damage constitutes a test failure.

16.3.3.6.6 Verification of susceptible MEE inside the HEMP barrier. Equipment in this category is located inside a HEMP barrier, which passes all applicable acceptance test criteria. Nevertheless, the equipment is found to malfunction during the verification tests. This is equipment that cannot withstand even the small internal residual stresses allowed under the standard. SPMs are used to harden such susceptible MEE.

The verification test requirements for these SPMs are governed by MIL-STD-188-125. The effectiveness of the SPMs is to be verified by demonstrating that the equipment will tolerate stresses at least 20 dB above the HEMP currents that could reach the MEE.

The most practical means of demonstrating the 20 dB margin is to perform PCI testing on the protected side of the barrier. Specifically, suppose that a malfunction is observed during verification testing, and the internal residual stress measured on a data line during external pulse drive is 0.1 A. Verification of the equipment hardness, after SPMs have been provided, can be accomplished by performing internal PCI tests. If the hardened system operates through pulses injected on the data lines inside the barrier at levels up to 10 times the residual (i.e. up to 1 A), then it satisfies the verification criterion. The pulse injected during internal PCI tests should be similar to the internal residual transient measured during external POE excitation. The criterion for similarity is that each of the norms (peak amplitude, peak rate of rise, rectified impulse and root action

integral) of the pulse injected during internal PCI testing should exceed the maximum corresponding norm for the residual transient measured during external PCI testing by a factor of at least 10.

16.3.3.6.7 Special protective volumes. The variety and extent of MEE falling into this category cannot be established until more experience with MIL-STD-188-125 testing is acquired. However, at least one case is presently known. Recent tests at hardened facilities show that some UHF antenna systems cannot meet the MIL-STD-188-125 acceptance test criterion (attenuation of a 250 A external stress to less than 1.0 A on the protected side of the POE protective device for a transmitting system). This specification cannot be met because the test waveform (and the HEMP stress) overlaps with the pass band of the antenna line protective device. Filters cannot be used to achieve the required attenuation without interfering with the operating signals, and nonlinear devices are not sufficiently effective to satisfy the criterion.

In such a case, a special protective barrier is erected so as to prevent the out-of-specification stresses from propagating into the protected volume. In this example, the coaxial antenna line shield and the rack containing the radio can be used to form a special protective barrier enclosing a special protective volume, where the residual stresses are higher than inside the protected volume. For verification, it is necessary to:

a. Verify that the SPB reduces stresses on the protected volume side of the barrier to within the stress control specifications of MIL-STD-188-125.

b. Verify by pulsed current injection testing that the MEE inside the SPV can withstand 10 times the residual stresses inside the SPV.

16.3.3.7 Statement of hardness verification. The criteria by which the HEMP hardness of a facility are to be judged are defined in MIL-STD-188-125. The requirement for a hardness statement is also defined in that standard. The appendices to the standard restate these criteria and the requirement for making a formal statement of the HEMP hardness of mission functions supported by the facility.

16.3.3.7.1 Hardness criteria. The facility hardness criteria as established in MIL-STD-188-125 fall into three categories: (1) internal transients (transients on conductors inside HEMP electromagnetic barriers) must be less than allowable levels, (2) no time-urgent, mission-aborting damage or upsets of MEE may occur during testing, and (3) POE protective devices must not be damaged or degraded as a result of verification testing.

16.3.3.7.2 Reporting requirements. Requirements for reporting the results of verification testing are presented in MIL-STD-188-125 and its appendices.

16.3.3.7.3 Discussion. MIL-STD-188-125 and its appendices require that, following verification testing, a definitive statement be made regarding the HEMP hardness of the facility and its mission-essential functions. Only two possibilities exist for the definitive statement. Either the facility is hard—it satisfies all of the hardness criteria--or the facility is not hard—it doesn't satisfy all of the hardness criteria. Thus, MIL-STD-188-125 does not allow the finding that a facility is hard to HEMP if all of the hardness criteria are not satisfied. Furthermore, it requires the acknowledgment of a vulnerability in the event of failure to satisfy any of the criteria.

In the event that the criteria are not all satisfied, the hardness statement should identify the specific vulnerability. This is because the standard requires that any vulnerabilities found during verification testing be eliminated. In the event that a condition leading to a vulnerability cannot be corrected, the only statement that can be supported according to MIL-STD-188-125 is that the facility is not hard to HEMP. The security classification of the hardness statement is assigned in accordance with the system security classification guide and DNA-EMP-1 (reference 16-7).

16.3.3.8 Other useful tests. The preceding paragraphs have described the tests prescribed by the standard for quality assurance, acceptance, and verification. This is the minimum set of tests required to establish the quality and effectiveness of the HEMP protection, provided that no deficiencies are found. Additional tests may be required to locate the cause of deficiencies, to establish the margin between the verification test levels and the susceptibility levels, and to diagnose system performance. It may also be prudent to perform additional quality assurance tests on components that have historically been failure-prone. In this section, some of these tests and test approaches are described.

16.3.3.8.1 Preliminary tests. Prior to installing components, it is advisable to perform functional tests to ascertain that these components meet their performance specifications. Large power filters (greater than 100 A), and custom designed rf signal filters are typical of components that should be tested before installation to ensure that the insertion loss, heat dissipation, and dielectric strength are adequate. These tests may be performed at the manufacturer's facility or at some other location, but acceptance of the component should be contingent on passing the tests. The tests involving heat dissipation must be of sufficient duration for equilibrium temperatures to be reached. Dielectric strength and other performance tests should be conducted at the equilibrium temperature.

Prior to conducting the pulse current injection tests for either acceptance or verification, it is good practice to perform low-level tests and measurements to determine that barrier elements, such as surge arresters and filters are installed and are at least functioning properly at low levels. Continuity checks and resistance measurements will reveal most

wiring errors. Continuous wave or low-level repetitive pulse tests are useful for measuring the in-situ attenuation of filters, optical isolators, and other barrier devices. Particularly in the verification test, the failure of a barrier device to attenuate the test pulse could be very expensive, since costly downstream MEE could be damaged. Hence, prior to the verification test, the performance of all barrier elements on electrical POEs should be established with low-level tests before the pulse current injection test is initiated. Then, high-level pulsed tests should be performed at gradually increasing drive levels to minimize the likelihood of catastrophic damage to system components.

16.3.3.8.2 Evaluation of safety margin. MIL-STD-188-125 does not require margins of safety be determined for a facility, but there are instances in which it is desirable to know this margin. For example, some safety margin must exist in order to allow for possible degradations in protection during system operation. If there were no safety margin, then hardness surveillance and maintenance actions would be required continuously to provide confidence in HEMP hardness. Clearly, this would be impractical. Therefore, hardness safety margins should be established and taken into account in designing the HEMP hardness surveillance and maintenance program.

The HEMP protection safety 'margin for a system is the ratio of the level of system-tolerable stress to the maximum level of stress that could be induced in or on the system by HEMP. Safety margin is generally expressed in units of decibels (dB), as defined by the equation:

$$\text{Safety Margin} = 20 \text{ x } \log\left(\frac{\text{minimum equipment strength}}{\text{maximum HEMP-induced stress}}\right) \tag{26}$$

A 20 dB safety margin implies that the stress tolerance level for the mission-essential equipment is a factor of 10 greater than the largest expected HEMP stress.

Because stresses can be transmitted to potentially susceptible equipment in a facility on any conducting line connected to the equipment, a separate margin will be associated with each individual conductor leading to each piece of equipment. The lowest safety margin of all conductors should be taken as the safety margin for that piece of equipment. Similarly, the smallest safety margin for any item of MEE in a facility or system should be viewed as the safety margin for the facility or system.

The level of stress that the system is able to tolerate can be established by:

a. Determining the ambient electrical stresses to which the equipment is routinely exposed and through which it continues to operate satisfactorily (HEMP understress method), or

b. Demonstrating tolerance to electrical overstress by:

1. Special overstress tests performed on the MEE, or
2. Acceptance tests used to confirm compliance with stress tolerance specifications, where such specifications have been imposed

The maximum level of stress that could be induced by HEMP on a conductor in a system hardened in accordance with MIL-STD-188-125 can be taken to be either the allowable residual stress as defined in the standard or the maximum stress observed on internal conductors during PCI testing. Since the observed stresses will be less than the allowable levels in a successfully hardened system, the second option will result in larger safety margins. Note that the effect of nonlinear protection at the POEs in the HEMP barrier are taken into account in the definition of safety margin. An increase in either the incident HEMP environment or the currents coupled to external conductors will not necessarily lead to a corresponding increase in stresses inside the barrier. The maximum level of stress that could be induced by HEMP on an item of MEE located outside of a HEMP barrier can be determined by the methods described in 16.3.3.6.5.

The safety margin of a system is most readily determined in those cases in which the stress tolerance of the MEE is controlled, for example, where MIL-STD-461 (reference 16-8) is invoked. If compliance with the specifications has been confirmed, the HEMP-induced stress measured during the pulse tests can be compared to the specified susceptibility levels to establish a margin without the need for additional equipment testing. However, nondevelopmental items are often used as MEE in C^4I facilities, and the stress tolerance or minimum susceptibility levels of such equipment are not controlled. Hence, this method of determining margins cannot be used for most facilities.

Where stress tolerance is not controlled, it can be inferred from special tests performed on equipment in the facility. The overstress test method requires that transients larger, by the desired margin, than the residuals measured inside the barrier during the verification testing be injected on conductors inside the barrier. If the MEE in the interior of the facility withstands an injected transient X dB larger than the measured residual, then the MEE can be said to have a safety margin of at least X dB.

In the understress method, the transient stress experienced during normal operation is measured and compared to the residual transients measured inside the barrier during the verification pulse testing. Again, if the residual transients are X dB smaller than the largest transients during normal operation, the MEE has at least an X dB safety margin.

All of the methods for determining the safety margin suffer uncertainties due to the fact that the equipment transient tolerance will be determined by testing with a waveform that differs from the HEMP-induced stress waveform. The HEMP-induced waveform will be different for each angle of incidence and polarization of the incident field, and hence there is no unique waveform. If the tolerance is determined from the MIL-STD-461 susceptibility tests CS10 or CS11, the test waveform is a set of damped sinusoids, rather than the waveform of any HEMP-induced residual inside the facility. Likewise, the HEMP-induced residual waveforms differ from the waveforms of the normal operating transients inside the HEMP barrier. Thus, some means of accounting for waveform differences is necessary for all three approaches. Selected parameters of the differing waveforms can be quantitatively compared for this purpose using the norm approach described in reference 16-9.

16.3.3 .8.2.1 Margin from overstress test. In this approach, the equipment tolerance is established by stressing the system interior to levels above the residual HEMP-induced stress using a direct injection pulse source inside the HEMP barrier. To establish a 20 dB margin, it is necessary to stress the interior of each POE to 20 dB above the transient stress measured when the verification test pulses were injected outside the barrier. In addition, it will be necessary to devise a system functional response monitoring capability to detect upset or damage. This can be quite challenging in fault-tolerant systems with many system states. However, an adequate system monitoring capability is required for verification purposes, even if margins are not established.

The effect of this overstress will depend on the system state and configuration at the time the overstress is applied. The response could be different for each of the many operating states. However, many measurements under operating conditions can be used to establish the statistical nature of the margin for a given configuration. If new equipment is installed or if existing equipment is rearranged, the response could also change.

16.3.3 .8.2.2 Margin from understress. In the understress approach, the amount by which the residual HEMP understresses MEE inside the HEMP barrier is used as the margin of safety. The ambient transient stress inside the barrier is measured inside the barrier at the same points at which the residual HEMP-induced stresses are measured (or at some point on each conductor leading from the corresponding POE to the MEE). Since the MEE tolerates even the largest of these ambient transients, the amount by which the largest transient exceeds the residual HEMP is a lower bound on the margin of safety for that MEE. To support this approach, transient monitoring instruments are installed to record selected norms of the operating transients inside the barrier. Measurements should be carried out for a period of several days to establish the tolerance of the system.

There will be a range of normal operating transients depending on the class of conductor being considered (e.g. electrical power conductors, data line, control lines) and their location within the facility. Because of this, residual HEMP stresses should be compared with ambient stresses measured for similar conductor classes and at a point located between the point of measurement of the HEMP residual and the MEE. Because of the variation in HEMP residuals and ambient stresses throughout a system, different safety margins are likely to be determined for different conductor types and locations inside the HEMP barrier. The minimum safety margin determined in this process should be considered to be the actual safety margin for the systems and missions being protected.

Defining the safety margin in terms of the HEMP understress avoids:

a. Possible latent damage to the system interior from overstress tests.

b. Possible misinterpretations resulting from undetected failures associated with untested sites.

c. Dependence of the margin on the stability of the MEE tolerance to stress.

It has the disadvantage that, in quiet systems, it may be difficult to establish a positive margin of safety. The ambient transient stress may be system-generated or it may be deliberately injected from time to time in an automated surveillance test. However, if stresses are deliberately injected, the first advantage-avoidance of risk of damage to equipment—is lost. If deliberately injected transients are used, these transients should not be so large that they reduce the mean time between failure of system components.

16.4 References.

16-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

16-2. Schaefer, R. R., and J. I. Lubell, "Validation of System Hardness to the Nuclear Electromagnetic Pulse (EMP)," DNA-TR-88-161, Defense Nuclear Agency, Washington, DC, 17 June 1988.

16-3. Casey, K. F., and R. R. Schaefer (Eds.), "The Electromagnetic Pulse (EMP) Threat from Nuclear Bursts at High Altitudes (U)," DNA-TR-87-093, Defense Nuclear Agency, Washington, DC, May 1986 (S-RD-N).

16-4. 'Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Environment (U)," DoD-STD-2169 (effective), Dept. of Defense, Washington, DC (S).

16-5. “Field Mapping Test of the DNA CW Antenna System,” DNA-TR-84-168, Defense Nuclear Agency, Washington, DC, 7 September 1983.

16-6. Schaefer, R. R., and J. Downing, “The HEMP Threat Relatability of Continuous Wave Field Illumination (CWFI) Testing,” DNA-TR-90-46, Defense Nuclear Agency, Washington, DC, 23 August 1989.

16-7. “Electromagnetic Pulse (EMP) Security Classification Guide (U),” DNA-EMP-1, Defense Nuclear Agency, Washington, DC, 1 December 1987 (S-RD).

16-8. ‘Military Standard - Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference,” MIL-STD-461 (effective), Dept. of Defense, Washington, DC.

16-9. Lubell, J. I., and R. E. Thomas, ‘An Approach to the Development of EMP Specifications and Standards Based on Norm Attributes,” DNA-TR-89-142, February 1990.

17. RELIABILITY, MAINTAINABILITY, AND TESTABILITY

17.1 Basic principles.

17.1.1 Reliability, maintainability, and testability principles. Reliability, maintainability, and testability are critical system design characteristics in determining effectiveness and readiness of the system to perform specified functions at all times during its operational life. If a high-altitude detonation occurs, site survival and successful mission completion will depend upon these characteristics of the HEMP protection subsystem.

Reliability refers to the ability of the system to perform its mission, when required, without failure, degradation, or excessive demand on the logistics support process. Quantitatively, reliability of a single unit is expressed in terms of its operating time and mean time between failures. The numerical reliability for a network of components which are functionally in series and parallel can be calculated from the individual unit reliabilities using well-known mathematical algorithms (references 17–1 and 17–2). These algorithms imply that high reliability can be achieved through the following techniques:

a. Considering both initial performance and degradation rates of components when allocating performance requirements, so that performance does not quickly fall below the “failure” threshold

b. Ensuring that components are evaluated under the environmental conditions and operational stresses through which they will be expected to function

c. Selecting components with large mean times between failures

d. Performing system failure analysis and combining components in an arrangement that is fault-tolerant

e. Conducting reliability tests and evaluations as needed to confirm the analyses

Even the most reliable system will occasionally require preventive and corrective maintenance to retain or restore its operational status. Maintainability is the ability of the item to be maintained at a satisfactory level of performance. Quantitative measures of this characteristic include the mean times between maintenance or between replacements, mean active preventive and corrective maintenance times, and logistics and administrative delay times. Maintenance cost factors including labor, parts, special support equipment, and personnel training are other critical parameters. The use of reliable components is perhaps the most important element in designing for maintainability. Maintenance downtime—the

sum of active maintenance, logistics delay, and administrative delay times—is minimized by providing effective diagnostic capability, easy access for maintenance, and readily available spares and tools.

The testability characteristic allows the operator or maintenance technician to determine whether the system is fully functional, operable at a degraded level of performance, or inoperable. It also includes the ability to isolate faults in a timely manner. Useful measures of testability are mean test time, system downtime for testing, fault detection and isolation times, and 'false (positive and negative) alarm" rates. Tasks in the testability design effort include identification of relevant status parameters to be continuously or periodically monitored, development of test methods, selection of built-in and portable test equipment required to obtain the measurements, and design of test point accesses.

MIL-STD-188-125 (reference 17–3) requires that reliability, maintainability, and testability be incorporated into the HEMP protection subsystem design. There is strong reliance on effective implementation in these technical areas for the hardening features at a C⁴I facility, because normal peacetime operations of the site may provide no feedback on the protection subsystem performance. The language of MIL-STD-188-125 also emphasizes the fact that reliability, maintainability, and testability are design characteristics. Technical principles of these disciplines are principally applied in the requirements and design development phases; the specified designs are then implemented and evaluated in the production/construction program.

Finally, it is noted that reliability, maintainability, and testability are conceptually separable, but have a high degree of interdependency. If the reliability is high, intervals between tests and maintenance actions can be long. A successful testability design minimizes the fault diagnosis element in corrective maintenance time. Good practices in all three areas conserve the life-cycle resources required to preserve mission survivability.

17.1.2 Reliability, maintainability, and testability source documents. Requirements in military acquisition programs for engineering specialty disciplines, such as survivability and supportability and including reliability, maintainability, and testability, are established at the DoD level and promulgated by the following documents:

a. DoD Directive 5000.1, 'Defense Acquisition" (reference 17–4)

b. DoD Instruction 5000.2, "Defense Acquisition Management Policies and Procedures" (reference 17–5)

These same references are cited elsewhere in this handbook as the origin of requirements for other support specialties, such as safety and human engineering (see section 18). Additional

information needed to implement these policies and procedures is provided in other DoD publications and military standards and handbooks.

General requirements and specific task descriptions for reliability programs during development, production, and initial deployment of military systems and equipment are provided in MIL-STD-785 (reference 17-6). One series of tasks involves the management area and includes planning, reviewing, and failure reporting. The second series contains design analysis and engineering efforts, and the demonstration tasks constitute the third set. The task descriptions are generic and include options for performance at various depths. Both selection of tasks and the depth of effort are intended to be tailored to the reliability needs of the particular system.

Other standardization documents assist the reliability engineer in performing the tasks. MIL-STD-756 (reference 17–1) and MIL-HDBK-217 (reference 17–7), for example, address reliability modeling and prediction. MIL-STD-781 (reference 17–8) concerns reliability testing. This list of references is not meant to be complete, and the DoDISS should be consulted to identify other applicable standards and specifications.

General information and task descriptions for maintainability programs are contained in MIL-STD-470 (reference 17–9). The maintainability tasks also cover the management, design studies, and demonstration areas, and they are intended to be tailored to specific system requirements. Maintainability prediction methods and design techniques are discussed in MIL-HDBK-472 (reference 17-10) and DoD-HDBK-791 (reference 17-11), respectively. Test methods and procedures are provided by MIL-STD-471 (reference 17–12).

Guidance for testability programs is supplied by MIL-STD-2165 (reference 17-13). Although the standard is primarily meant to apply to electronic equipment, the basic task concepts are equally applicable to designs for the HEMP shield and mechanical POE protective devices. Testability demonstrations are actually performed as part of maintainability test and evaluation.

One additional standard, MIL-STD-721 (reference 17–14), is also recommended reading for individuals with limited experience in these areas. This document defines technical terms used in the reliability, maintainability, and testability disciplines.

The HEMP program manager for facility acquisition phases (see section 21) has major responsibilities in tailoring reliability, maintainability, and testability tasks to the HEMP protection subsystem application. Facility requirements documentation provided to the design agency identifies the need to incorporate principles of these disciplines. Depth and quality of the work are monitored through periodic reviews during design and construction.

The HEMP program manager should also ensure that maintenance procedures, testing, spares, and configuration management sections of the HM/HS plan reflect the results of the reliability, maintainability, and testability efforts.

17.2 Reliability and maintainability.

17.2.1 MIL-STD-188-125 requirements.

5.1.9 Reliability and maintainability. The HEMP protection subsystem shall be designed and constructed to be rugged, reliable, and maintainable. Reliability and maintainability program tasks and requirements shall be included in the facility acquisition specifications to assure that reliability is considered in component selections, to reduce the frequency, complexity, and costs of design-dictated maintenance, and to provide adequate provisioning with spare hardness critical items and maintenance tools and supplies.

The mission-critical systems of a time-urgent C[4]I facility, including the HEMP protection subsystem when HEMP survivability is an operational requirement, have very stringent restrictions on both planned and unscheduled downtime. These constraints are necessary because the site may be required to respond to events within seconds or minutes. Reliability and maintainability requirements are therefore imposed by MIL-STD-188-125. High HCI reliability translates into high probability that the performance of the protection subsystem will be adequate to prevent mission-aborting upset and damage in the DoD-STD-2169 HEMP environment (reference 17-15). A maintainable design is required so that hardness can be quickly restored if HCI failure or excessive degradation occurs.

The explicit reliability and maintainability requirements in MIL-STD-188-125 also highlight the need for more formal reliability and maintainability programs than those customarily specified for building design and military construction projects. Similar intent is reflected in the language concerning provisioning.

The remainder of subsection 17.2 provides general guidelines and specific recommendations for satisfying the reliability and maintainability requirements. The design agency and architect-engineer bear most of the responsibility for incorporating reliability and maintainability measures. The command that prepares the facility requirements and the construction team also play important roles. The reliability, maintainability, and provisioning analyses may be performed within the scope of the design contract or as part of a separate logistics effort.

17.2.2 General design guidance. For many shielded facilities, the major reliability and maintainability difficulties are associated with the shield itself. The problems occur

when the shield is formed with mechanical joints between adjacent metal sheets or panels. Joining techniques employing clamps, bolts, or rivets produce electromagnetic seals of inherently lower quality than the basic sheet material. Furthermore, oxidation, moisture, and accumulations of dirt and grease in the metal-to-metal contact area will cause gradual performance degradation. Any requirement for periodic refurbishment of the seams-a 1000 m^2(floor area) shielded enclosure will typically have 150 linear meters of seams—would be clearly intolerable.

The seam problem has been circumvented for MIL-STD-188-125 facilities by requiring welded or brazed seams (see section 8). These joints, when properly made initially, are as high in electromagnetic quality, as resistant to gradual degradation, and as undemanding of maintenance as the basic shield material. Welded and brazed shields meet the ruggedness criterion when adequately secured to and supported by the structural members. They are also reliable and will leak electromagnetically only if a crack or hole develops.

Preventive maintenance requirements on a welded or brazed shield (not including the POEs) are reduced to eliminating environmental conditions that promote corrosion and monitoring for faults. Corrosion control issues and measures are addressed in handbook section 15. The occurrence of personnel-induced shield faults can be minimized through training and configuration management.

The HEMP reliability and maintainability program can therefore focus on POE treatments and special protective measures. As frequently mentioned throughout this handbook, the concerns can be erased by eliminating the POE or special protective requirement. Elimination of avoidable penetrations and SPMs should therefore be given high priority.

When a penetration cannot be eliminated, reliability and maintainability should be factors in the protective device design. If it is feasible to choose between the type of penetration, the most reliable and maintainable type should be selected (see table XIX). A fiber optic penetration should thus be used in preference to a penetrating electrical wire POE, and heavy-gauge, welded waveguide array protection should be chosen for ventilation POEs over honeycomb waveguide panels where possible.

POE protective devices should be protected from exposure to rain and direct sunlight in a temperature and humidity controlled environment. One of the most severe maintainability problems encountered at many sites has occurred when one side of the device is in the climate-controlled protected volume, while the other side is environmentally uncontrolled. Condensation and rapid HCI corrosion results. If conduits and waveguides between environmentally controlled and uncontrolled areas cannot be avoided, they should be sealed with fire-retardant and nonconductive material to prevent air flow.

TABLE XIX. Penetration ratings by reliability/maintainability.

Type of Penetration	Reliability/Maintainability
Ž Aperture penetration with welded access cover	Most reliable and maintainable
Ž Waveguide-below-cutoff piping penetration	
Ž rf communications waveguide-below-cutoff welded to the shield	
Ž Waveguide-below-cutoff fiber optic penetration	
Ž Heavy-gauge, welded waveguide-below-cutoff array	
Ž Aperture penetration with mechanically fastened access cover or rf communications waveguide mechanically fastened to the shield	
Ž Light-gauge (honeycomb) waveguide-below-cutoff array	
Ž Electrical penetration with filter/ESA protection	
Ž Shielded door penetration	Least reliable and maintainable

Hardness critical assemblies such as filters, surge arresters, and shielded doors, which are usually purchased from a supplier, should be chosen on bases of verifiable history of successful in-service use and known high mean times between failures. Appropriate requirements can be written into the architect-engineer's scope of work and the construction specifications for evidence of satisfactory performance in other facilities and applications.

Designs for the installation of POE protective devices must also consider reliability and maintainability. If the device can be welded (or brazed) into place at the barrier penetration, this method should be employed. The design must also provide access for performing maintenance and inspections. As examples, there must be access into ventilation ducts to inspect ventilation POE protection and sufficient clearance to open the covers of filter/ESA enclosures. Frames for the protective devices must be designed to prevent warpage due to mechanical and thermal installation stresses, and covers must operate easily under all expected temperature variations.

Designs for SPMs are so variable that it is difficult to provide explicit guidance. It is simply noted here that reliability and maintainability must be considered.

17.2.3 Reliability and maintainability programs. Formal reliability and maintainability programs in accordance with MIL-STD-785 and MIL-STD-470 are not usually required in military construction projects. If such programs are established for other aspects of building design and construction, however, the HEMP protection subsystem should be included. If not, it is recommended that formal reliability and maintainability programs exclusively for the HEMP protection be specified during the design phase of MIL-STD-188-125 facilities. The suggested tasks are as follows:

a. MIL-STD-785, task 101 – establishes the requirements for the reliability program and for development of a program plan

b. MIL-STD-785, task 203 – reliability predictions

c. MIL-STD-470, paragraph 5.1 – establishes the maintainability program and program plan requirement

d. MIL-STD-470, paragraph 5.2- maintainability analysis

e. MIL-STD-470, paragraph 5.6 – maintainability prediction

Quantitative reliability and maintainability requirements or objectives for the HEMP protection must be provided in the facility requirements document. Mean times between failures of at least five years are reasonable for HCIs, provided that scheduled maintenance

is performed. Suggested mean time between maintenance intervals are three months for shielded doors and at least one year for other components.

Reliability and maintainability can be addressed in a common program plan, and testability planning can be included in the same document (see 17.3.2). A relatively low-level program to estimate mean time between failures and maintenance values, with documented sources and rationale for the figures, is envisioned. The plan should describe the program to be performed, the contractor's approach, and the data to be acquired. It should be prepared in accordance with DI-R-7079 (reliability), DI-MNTY-80822 (maintainability), and DI-T-7198 (testability).

Results of these programs in terms of performance, reliability /maintainability parameters, and demonstration requirements should be reflected in the architect-engineer's design drawings and in the provisions of the construction specifications. In particular, construction contractor submittals for HCIs must show that the selected products meet all requirements including reliability and maintainability provisions. Since the drawings and specifications are the requirements for the construction agency and contractor, formal reliability and maintainability programs in accordance with the military standards are not considered necessary in the construction phase. The construction agent's on-site representative must ensure that the reliability and maintainability design features are properly implemented by the construction contractor.

17.2.4 Provisioning.

17.2.4.1 Spares and repair parts. The ability to quickly restore the HEMP protection subsystem to a satisfactory condition after an HCI failure implies that replacement parts and repair materials and supplies must be readily accessible. Items that may be required on short notice for emergency repair of serious hardening deficiencies should be locally stocked. Other spare HCIs that can be shipped to the site within the time interval necessary for assembling the repair team may be held in a central inventory. Still others will be purchased from commercial sources, when needed, if acceptable delivery schedules are assured.

The level of required local provisioning is determined by the number of installed HCIs of each make and model, their reliabilities, and their replacement times. Estimates of mean times between failures will be predicted in the recommended reliability analyses. Procurement lead times vary greatly from item to item and manufacturer to manufacturer. Vendors seldom maintain shelf stocks of high-current filters, for example, and they produce a particular line of components at widely spaced intervals. Delivery time for a new filter may therefore be six months or more. A list of organizational spares and repair parts is

developed from design and logistics information collected during the design and construction phases and included in the HM/HS program documentation. These items should be provided to site personnel when they assume maintenance responsibility for the system.

Based upon past experience at HEMP-hardened facilities, suggested provisioning guidelines can be provided. The local inventory should include the following:

a. Cleaning kits, supplies, and repair parts for at least two years of normal maintenance on shielded doors

b. At least 200 percent spares for each type of rf gasket used in the HEMP protection subsystem; sheet or roll materials from which the gaskets may be cut are acceptable

c. At least 10 percent spares for each type of filter and ESA installed at the site; a larger quantity should be provided when there is a history of reliability problems

As site-specific experience is accumulated, the list should be appropriately adjusted. It is also recommended that records of in-service HCI failures and maintainability problems be maintained by individual HEMP-hardened sites and collected at the military department level. The information can then be used to improve the accuracy of reliability and maintainability predictions and to upgrade the quality of HM and HS programs.

When practical, spare HCIs should be built into the POE protective device. The enclosure of a filter/ESA assembly, in particular, should be large enough to store appropriate spare components. The spare filters and ESAs should be mounted in a configuration that does not require any barrier penetrations. Dedicated storage should be provided for all other items, to avoid loss and damage that inevitably occur with unsecured components.

Finally, the HEMP protection subsystem should be designed to minimize the number of different types of HCIs and spares. While little standardization of these items currently exists, the creation of qualified products programs for HCIs is encouraged.

17.2.4.2 Special tools and test equipment. Special tools and test equipment required to operate and maintain the HEMP protection subsystem must be identified during design and construction and be provided to the site at system turnover.

Special tools increase the costs and complexity of maintenance and dictate greater personnel skills, and should therefore be avoided. As a general rule, the HEMP hardening design can be made compatible with standard tools with the possible exception of those needed for shielded door maintenance. Adjustment, cleaning, and refurbishment procedures should be considered when selecting the shielded door supplier.

Military service policies on the level of organizational testing capability will define the special test equipment needs. SELDS (or "sniffer") equipments operating at shielding effectiveness magnetic and plane wave frequencies are recommended for all facilities with high-quality electromagnetic barriers.

The magnetic field and plane wave SELDS instruments are each commercially available at unit costs of a few thousand dollars. Magnetic models operate at a frequency of the order of 100 kHz. They are most commonly employed as a direct current injection source to excite one side of a shield, while the opposite surface is surveyed with an rf probe to detect field leakage. Some models are also supplied with a radiating antenna for illumination testing. Built-in shield monitoring approaches that use this instrument are discussed in 17.3.5.

Plane wave "sniffers" typically operate at 400-500 MHz, and they are highly portable illumination test sets. The higher operating frequency makes them particularly useful for pinpointing fault locations.

If the site is to have the capability to perform procedures specified in the MIL-STD-188-125 appendices, additional test equipment will be required. These methods are employed for periodic hardness surveillance/reverification and for acceptance testing after HEMP protection subsystem repairs. They require a physically large and expensive inventory of simulation sources and instrumentation. It is anticipated, therefore, that this capability will generally be implemented at a depot level.

17.3 Testability.

17.3.1 MIL-STD-188-125 requirements.

> 5.1.11 Testability. The HEMP protection subsystem shall be designed and constructed to accommodate quality assurance, acceptance, and verification testing and hardness maintenance and hardness surveillance. The facility shield shall be accessible for visual inspection at all POEs. Access for periodic shielding effectiveness measurements shall be provided except on the floor shield of a bottom floor and on buried facilities. The built-in shield monitoring capability shall consist *of* a permanently installed large loop or a permanently installed shield injection point system, as described in MIL-HDBK-423, or other exciter and sensor elements which will detect significant changes in the electromagnetic barrier performance. Electrical POE protective devices shall be installed with accessible pulsed current injection drive points and measurement points.

Since ground-based C[4]I facilities do not experience HEMP-like stresses in the course of routine peacetime operations, readiness of the HEMP protection subsystem cannot be inferred from successful conduct of daily mission functions. Nevertheless, HCIs are expected to continuously provide a level of performance that protects the site from a HEMP event. Periodic inspections and tests are necessary to obtain the status information required to support the survivability objective.

The testability requirements in MIL-STD-188-125 are intended to ensure that technically credible testing and HM/HS programs can be performed cost-effectively. Methods for satisfying the requirements are discussed in succeeding paragraphs of this section. The basic concepts are those of good design logic and practice, as follows:

a. Determine HCI performance requirements (electromagnetic requirements for HEMP protection, functional requirements as an element in the communication-electronics system, operating environment requirements, etc.).

b. Identify test methods for performance monitoring and the design features needed to support testing.

c. Identify maintenance and surveillance requirements and the design features needed to support HM/HS.

d. Provide a design which meets the performance requirements, while accommodating testing and HM/HS.

Faithful application of this approach will result in adequate access for inspection and installation of test connections. Additionally, sufficient space will be provided for sensors and repetitively required test fixtures in the initial construction.

17.3.2 General design guidance. MIL-STD-188-125 explicitly requires that the HEMP protection subsystem be designed and constructed to facilitate testing and HM/HS. Hardness quality assurance, acceptance, and verification test requirements and methods are described in the MIL-STD-188-125 appendices and handbook section 16. Section 20 addresses the HM/HS program. The HEMP subsystem designer should become sufficiently familiar with the test, maintenance, and inspection techniques that the necessary accommodations can be provided.

Identification of performance parameters to be monitored for acceptance and verification of HCIs that comprise the electromagnetic barrier—the shield and POE protective devices-has essentially been done in MIL-STD-188-125. The test equipment and data

requirements are also specified. The responsibilities of the designer and construction contractor in support of the acceptance and verification test programs are therefore to provide space and access for simulation sources, convenient points for signal injection and monitoring, ports for sensor data extraction, and plans for tests of SPMs.

Planning for acceptance and verification testing for SPMs must be an integral part of the design process. As each special HCI is specified, a concept for measuring its performance should be developed and the required test accommodations should be designed.

The HM and HS programs require periodic physical inspections of all hardness critical items and assemblies, relatively simple system performance measurements at the site organizational level, and more sophisticated surveillance/reverification tests. The hardness surveillance/reverification procedures are generally the same or similar to the methods employed in the original verification program. Thus, the measures provided to accommo date verification testing will be used repetitively and should be permanent, rather than temporary.

Subsection 17.3.3 discusses access for visual inspections of the HEMP shield and the POE protective treatments. Testability requirements for shielding effectiveness measurements are addressed in 17.3.4 and concepts for the required built-in shield monitoring system are presented in 17.3.5. Integration of these three elements of the testability design is essential since all three involve the same zones adjacent to the electromagnetic barrier.

Pulsed current injection testability, including the arrangement of the penetration entry area to accommodate the PCI pulse delivery systems, is discussed in 17.3.6. Subsection 17.3.7 addresses cw immersion testability, which is one of the factors to be considered in the site selection process for the facility.

A formal testability program in accordance with MIL-STD-2165 is recommended during the facility design phase. The program should be performed at a depth comparable to the reliability and maintainability programs discussed in 17.2.3 and should include task 101 (Testability Program Planning) and task 202 (Testability Preliminary Design and Analysis).

17.3.3 Access for visual inspection. The recommended HM/HS program (see section 20) requires maintenance personnel at MIL-STD-188-125 HEMP-hardened facilities to routinely inspect the integrity of the barrier and the condition of each POE protective device. Access to perform these inspections must therefore be provided in the building design. Elements of access include both location and configuration of enclosures.

Access to both sides of the entire shield surface (except the underside of a ground floor shield) is highly desirable. The designer provides this access, where possible, by reserving a zone approximately 1 m (3.3 ft) in width between the outer structure and the shield walls. A similar clear zone is required between the roof deck and the ceiling shield. Additionally, equipment inside the barrier should be placed at least one meter from the shield surface, where possible. Interior wall finishes may be used, but the panels should be easily removable for inspection and testing (painting the shield for purposes of corrosion protection is not precluded). This overall building concept is illustrated and described in greater detail in section 11. The design for visual access to the shield must be coordinated with the requirements for shielding effectiveness testability (see 17.3.4).

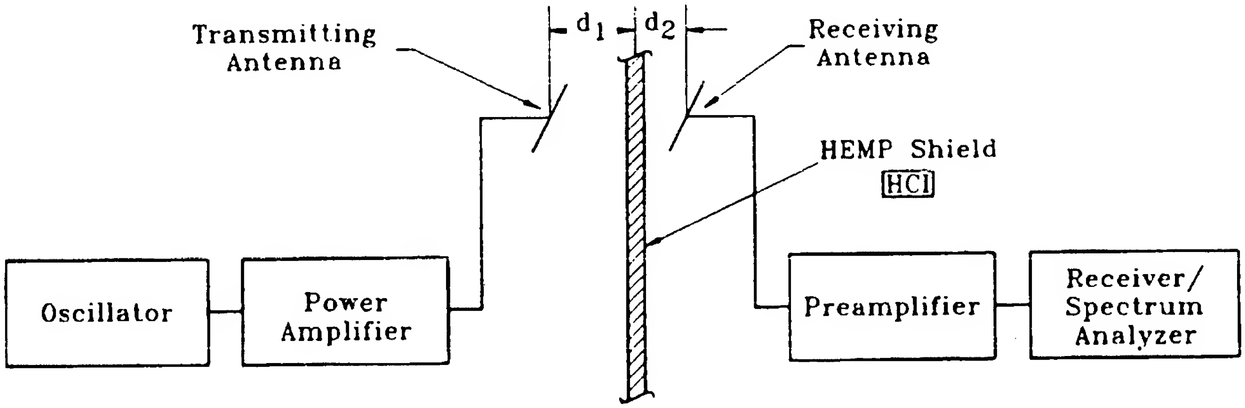
Visual access to as much of the shield surface area as possible should be provided, when it is not practical to provide such access to the entire surface. At least the minimum requirements of MIL-STD-188-125 must be satisfied. These minimum requirements include access for visual inspection at all POEs and the crawl space between the roof deck and the ceiling shield.

Each POE protective device should be mounted in a position where it can be easily and safely inspected, preferably while the inspector is standing on the floor. If it is necessary to mount an HCI high on the wall or on the ceiling, a means such as a safety platform and ladder for safely working on the device must also be provided.

Ventilation WBC arrays may be in closed duct systems, and filter/surge arresters will be installed in electrical enclosures. Access covers should be designed in accordance with human engineering principles (see section 18), with quick-opening captive fasteners and sufficient clearance to fully open hinged covers and to remove bolted cover plates.

17.3.4 Shielding effectiveness testability. The shielding effectiveness measurement technique is established by appendix A of MIL-STD-188-125 and is illustrated in figure 169. One side of the HEMP shield surface is illuminated with electromagnetic energy radiated at a prescribed frequency by the transmitting antenna. An area on the opposite side of the shield is surveyed using the receiving antenna to detect the fields that diffuse through the shield or leak through a defect. It is common, but not required, that the transmitting antenna is placed outside the electromagnetic barrier and receiving antenna is located within the protected volume. Shielding effectiveness testability implies that the measurements can be made in accordance with required procedures.

The essence of designing for shielding effectiveness testability is reserving space on both sides of the shield so that the antennas can be positioned at the required locations. The arrangement illustrated in figure 170 and described below provides inspectability of all

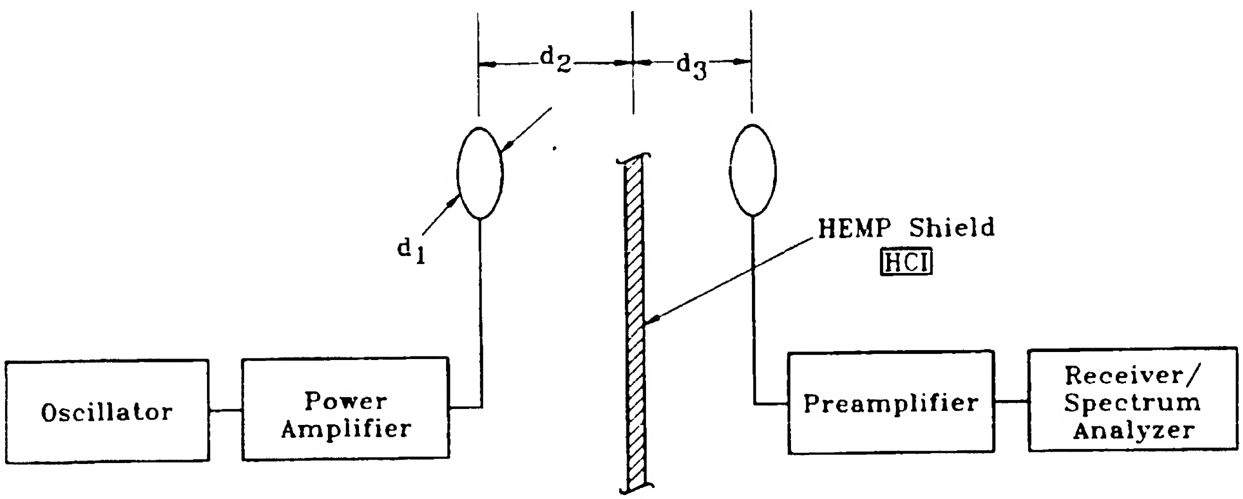


Calibration Spacing $\geq$ 2.5 m

d_1 = Calibration spacing − 30 cm

d_2 = 30 cm (Stationary Measurement)
= 5 cm to 60 cm (Swept Measurement)

a. **Plane wave test configurations.**



Calibration Spacing $\geq$ 1.25 m

d_1 − Loop diameter

d_2 = Calibration spacing − 30 cm

d_3 = 30 cm (Stationary Measurement)
= 5 cm to 60 cm (Swept Measurement)

b. **Magnetic field test configurations.**

FIGURE 169. Shielding effectiveness tests.

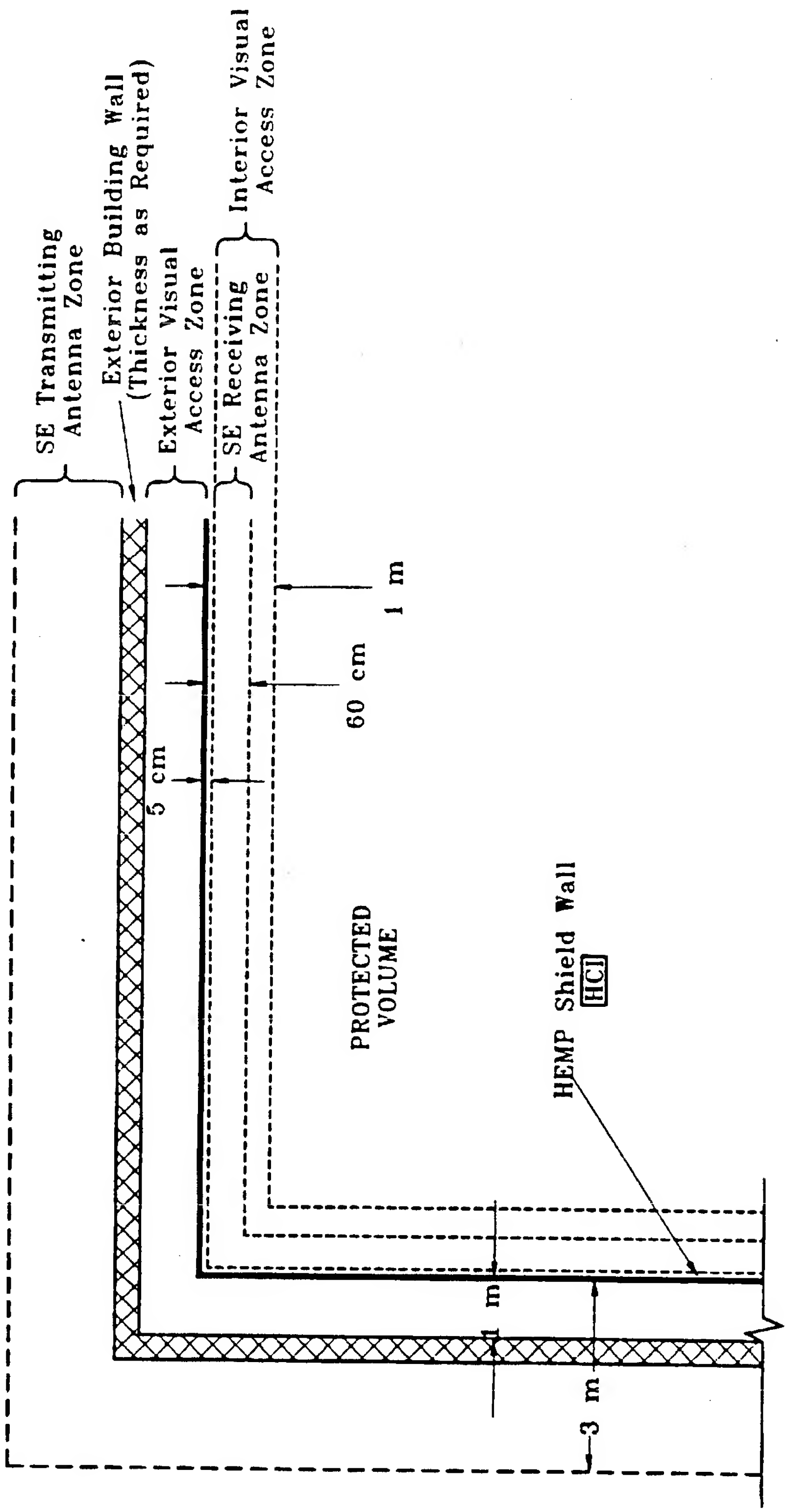


FIGURE 170. Clear volumes for shielding effectiveness testability.

barrier surfaces, as well as the capability to perform shielding effectiveness measurements. It is configured for the SE transmitting antennas to be outside the shield.

The exterior building and the shielded enclosure are separate structures, as recommended in this handbook. The l-m (3.3-ft) spacing between the building wall and the HEMP shield creates the “clear volume,” from which the outer barrier surface can be inspected and maintained. Another clear volume is established inside the HEMP enclosure, by placing the interior equipment at least 1 m from the shield.

The locations of SE transmitting antennas with respect to the shield are defined in planes that are parallel to and at least specified distances from the steel surface [at least 2.2 m (7.2 ft) for the plane wave measurements and 0.95 m (3.1 ft) for magnetic field measurements].[10] The region between the exterior building wall and the plane at 3 m from the shield should be as free from obstructions as practical, so that the transmitting antennas can be positioned in this zone. Equipment such as heat exchangers, fences, and other objects should be placed beyond the 3-m plane, if possible.

The receiving antenna locations are denoted as “stationary” and “swept-in-space.” The stationary positions are 30 cm (1 ft) from the inner shield surface. The swept measurements are made by moving the receiving antenna through the volume extending from 5 cm (2 in) to 60 cm (2 ft) from the shield. Therefore, this zone should also be free of objects that interfere with the antenna movements.

The clear volume requirements apply at the walls and ceiling of a ground floor shield, and they apply on all six sides when possible. For a buried facility, the clear volume requirement should be satisfied at least in the penetration entry area and in the vicinity of other barrier POEs.

When performing shielding effectiveness measurements and other tests prescribed by MIL-STD-188-125, transmission of test signals through the electromagnetic barrier may be necessary. It is recommended that two 2.5 cm (1 in) diameter waveguid-below-cutoff penetrations for fiber optic cables and four N-type bulkhead feedthrough connectors be provided for this purpose. The test POEs should be located in the environmentally controlled penetration entry area, and they should be sealed when testing is not being conducted. Figure 171 illustrates one possible design of the test feedthrough feature. The outer compartment of the test penetration panel should be weather-tight, to prevent

10 Note that the position of the exterior building wall in figure 170 forces the spacing for the magnetic SE measurements to be somewhat greater than the minimum allowable distance. It may be necessary to increase the output power of the transmitter amplifier to meet the dynamic range requirement for this larger spacing.

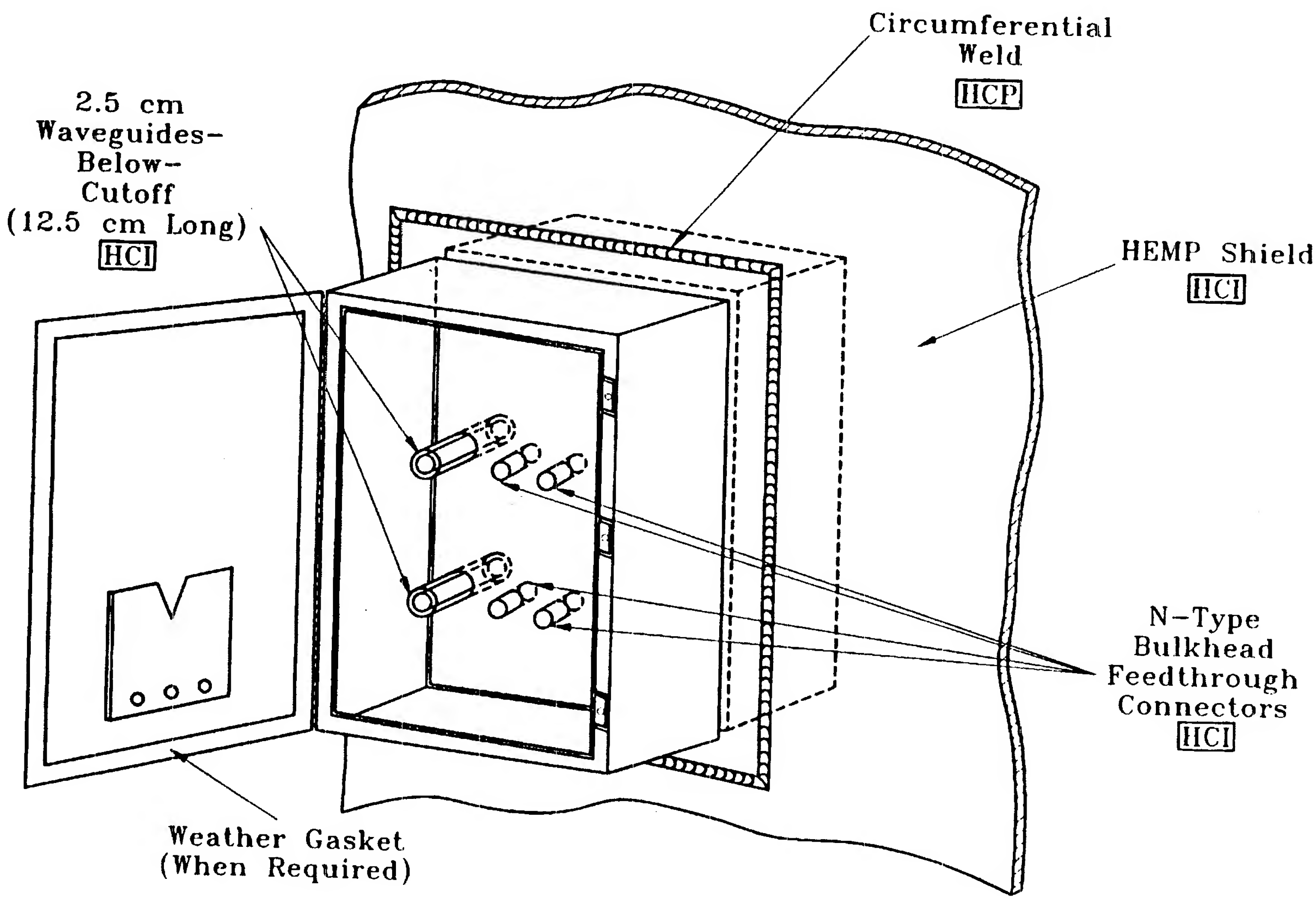


FIGURE 171. **Test penetrations.**

exchange of air through the waveguides and accompanying condensation, if it is located in an uncontrolled environment.

17.3.5 Built-in shield monitor. A built-in shield test capability is required by MIL-STD-188-125. The monitoring system must provide at least qualitative indications of a significant change in the electromagnetic barrier performance.

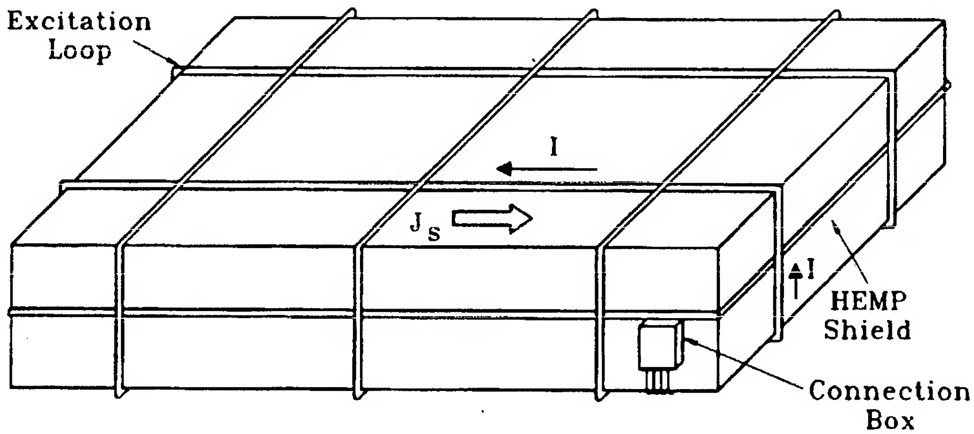
This subsection discusses both qualitative and quantitative shield monitors. A quantitative monitoring system is one that induces a surface current density (J_s) of known amplitude on the outer surface of the shield. A measurement of the surface current density or field strength on the inner shield surface will therefore yield a quantitative value for the attenuation. If the external surface current density is not known with reasonable accuracy, only a qualitative leak/no leak finding can be made.

Qualitative systems have been provided on numerous large, fixed, ground-based C^4I facilities. An empirically quantitative system has been realized with at least one of these installations by measuring the induced external surface current density over part of the shield. Fully quantitative systems have been studied in analyses and laboratory experiments but, as of this handbook publication date, none have been implemented on large buildings.

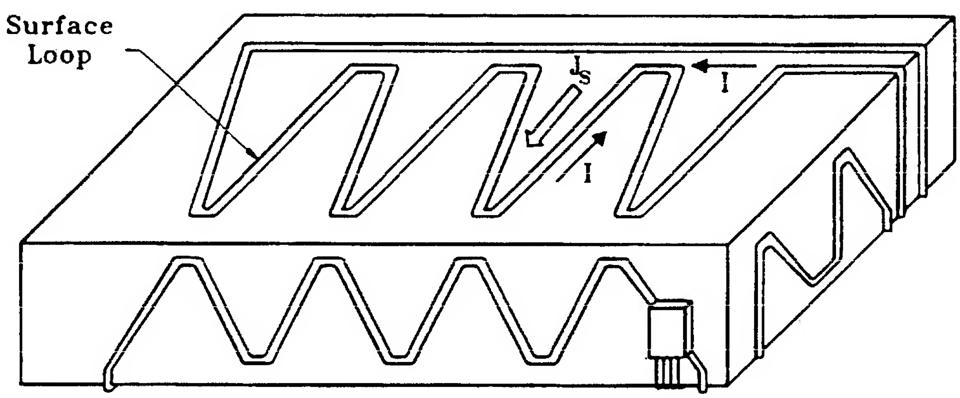
17.3.5.1 Qualitative monitoring systems. Three possible designs for a built-in, qualitative shield monitoring system are shown by figure 172. The first design, the building loop system, employs several independent loops of unshielded insulated wire around the entire building. The wiring is typically in plastic conduit, a few centimeters from the shield surface. Coverage is maximized by providing loops in each of the three orthogonal orientations. Drive wires for all loops are routed to terminal pairs in a common junction box, where the source is connected.

The loops are excited, one at a time, with a low frequency oscillator and power amplifier to produce a loop current (I) of the order of 1–10 A. The operating frequency or frequencies (the frequency may be fixed or stepped) are in the range of 100-1000 kHz, since the loop circumference should be a small fraction of the wavelength. Current through the loop induces a surface current density on the outside of the shield, and the inner surface is surveyed with an rf probe to check for field leakage. A magnetic SELDS instrument (see 17.2.4.2) is often used as the source and detection probe. Reference 17–16 describes and evaluates an installed large loop monitoring system.

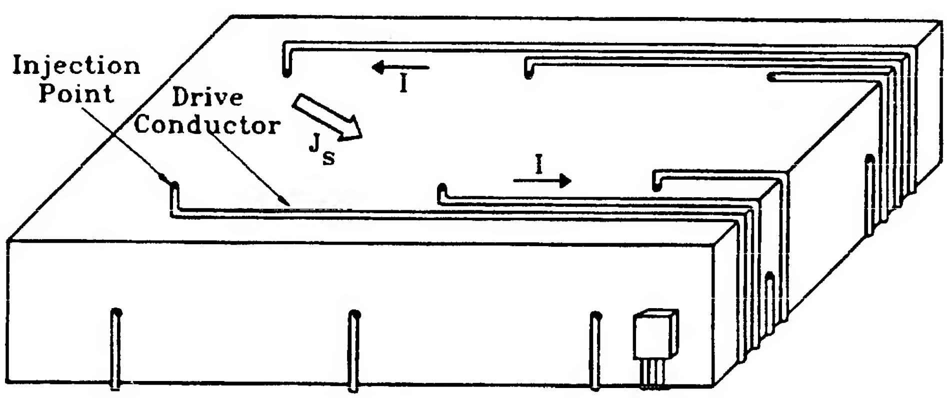
The electromagnetic fields that leak through a small aperture in the shield to the interior rapidly decrease in strength with increasing distance from the fault. The inner



a. Building loop system.



b. Surface loop system.



c. Direct injection system.

FIGURE 172. Built-in shield monitoring systems.

surface must therefore be surveyed with the detector very close to the shield. Thus, effective use of the built-in monitoring system requires the same degree of shield access needed for visual inspections and shielding effectiveness measurements.

In part, the loop system is qualitative because the magnitude of J_s decreases approximately as the square of the distance from the loop conductor. For this reason, parallel loops should be provided with separations of about 2.5 m (8.2 ft). Furthermore, the surface current density is strongly affected by the presence of other conductors (electrical wiring, metal pipes, building structural members) in the vicinity. Because of these variations, measurements must be interpreted by comparing them with previous readings made after a successful acceptance or HEMP verification test, when the shield was known to be performing satisfactorily.

The surface loop design, shown in figure 172b, uses loops formed by 'snaking" an insulated wire across the surface to be monitored. The surface loop could be a simple rectangle, but sensitivity is improved with a more complex layout such as that illustrated in the drawing. Excitation of the system is identical to the drive method previously described for building loops. Again, J_s induced by the surface loop varies with distance from the driven wire, and perturbations to the distribution are produced by the presence of other conductors.

A shield injection point system is illustrated in figure 172c. The injection points may be at the corners of the building, along wall-ceiling, wall-floor, and wall-wall seams; and at intermediate points on the surfaces. Differential drive between two adjacent injection points forces a current to flow on the shield. Surface current density will be very large near the injection points, and much lower J_s values will exist at locations between the connections. The distribution is also strongly influenced by the routing of the drive cables, as well as other proximate conductors. Injection points are typically arranged in a grid with about 20-m (66-ft) spacings.

All of the designs described here have been installed on one or more HEMP-shielded facilities and have proven to be effective in detecting faults. Also, they all have some shortcomings that limit the completeness of their coverage. No comparative studies of effectiveness and cost of the different approaches have been identified to date.

A fourth design uses one or more transmitting antennas to illuminate the shield from locations outside the barrier. Leak detection is performed with receiving antennas inside the protected volume. A commercially available version of this system operates at a frequency of approximately 900 MHz.

17.3.5.2 Quantitative monitoring systems. Analytical and experimental studies aimed at developing designs for a built-in quantitative shield monitoring system have been undertaken by various centers for HEMP expertise. One proposed concept employs closely coupled transmitting and receiving antennas on opposite sides of the barrier. Another approach, which has been partially implemented on small deployed enclosures, uses the outer shield surface as one side of a strip transmission line. Fully automated monitoring systems have also been studied and prototype. To date, however, these designs have not advanced to a stage where use in a military construction program can be recommended.

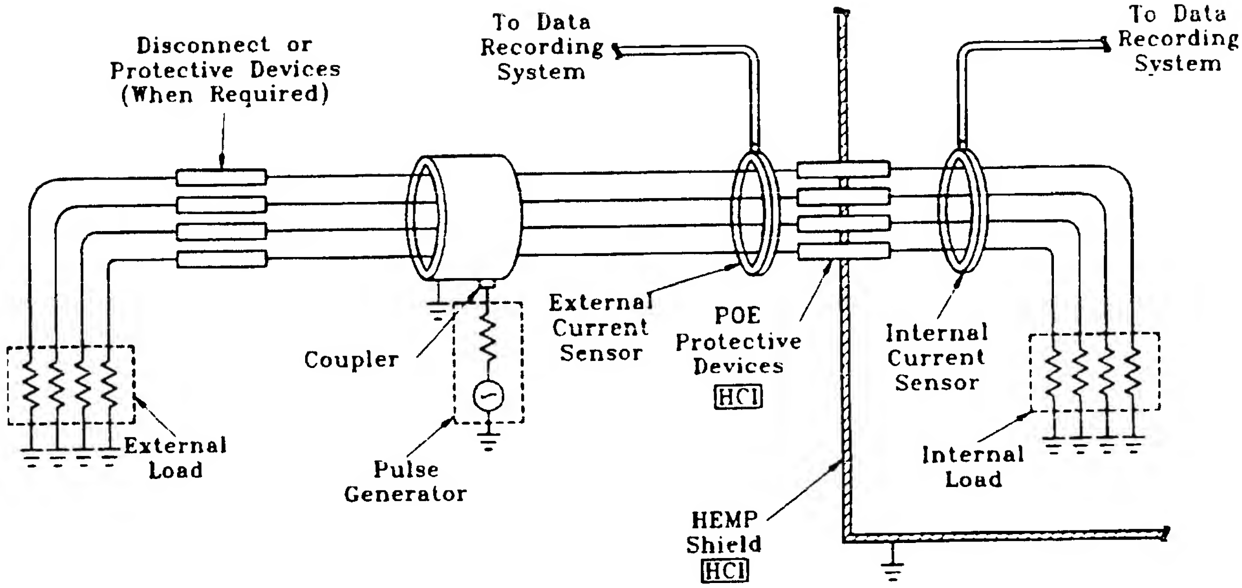
The best presently available approach for quantitative shield performance monitoring with a built-in-system is the empirical technique discussed in reference 17–16. One of the types of systems previously illustrated in figure 172 is implemented, and the external surface current density distribution is then determined by mapping. It should be recognized that the distribution will be nonuniform and, in some areas, the measurement dynamic range is likely to be less than the shielding effectiveness requirement.

It has also been proposed that a qualitative system can be calibrated using MIL-STD-188-125 shielding effectiveness data, and changes in the measurements can then be quantitatively interpreted. A technically comprehensive evaluation of this possibility has not been performed to date.

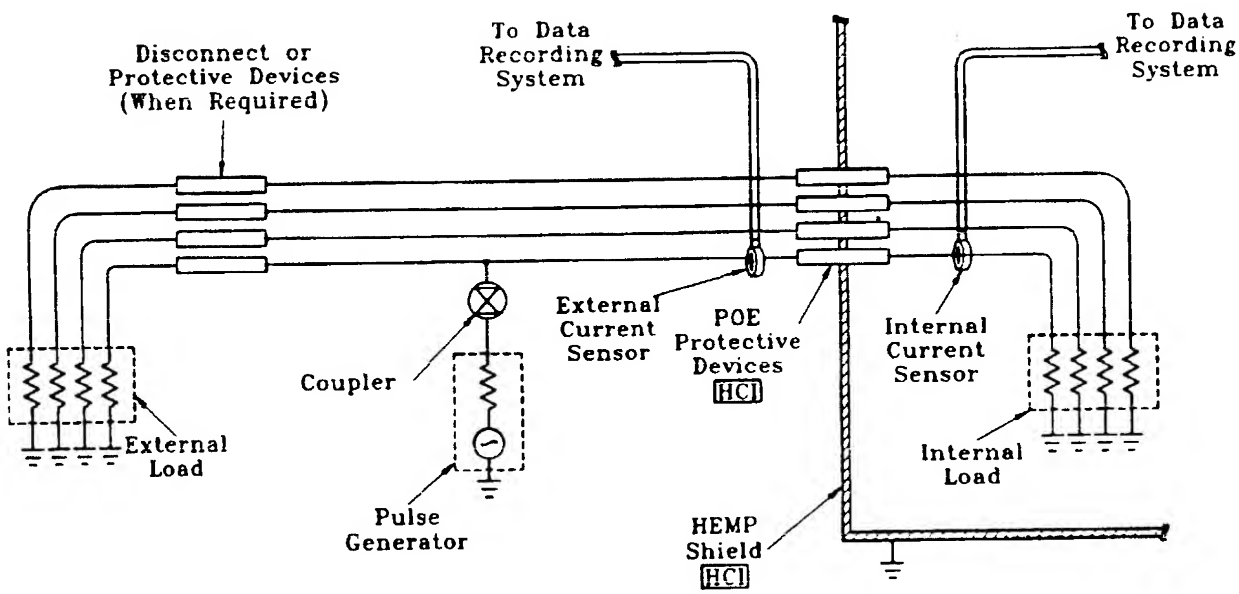
17.3.6 Pulsed current injection testability. Requirements and procedures for PCI testing on electrical POE protective devices are established in appendix B of MIL-STD-188-125 and further discussed in handbook section 16. Schematic illustrations of the test configurations are presented in figure 173. This subsection addresses facility design features to facilitate efficient execution of the PCI procedures.

17.3.6.1 Circuit flexibility. Circuits containing components to be PCI tested must ordinarily be shut down during installation and removal of sensors and pulse delivery system connections. The facility should be designed with sufficient flexibility and switching that electrical POE protective devices can be deenergized, one at a time, without disrupting the mission.

The flexibility will often be provided by a standby unit. Electrical power can be supplied by the backup generators when testing the commercial power line POE protective device. There is usually a sufficient number of installed heat exchangers to carry the facility cooling load with one unit shut down. Electrical penetrations for the different units should use separate filter/ESA assemblies that can be independently deenergized.



a. Common mode test configuration.



b. Wire-to-ground test configuration.

FIGURE 173. Typical PCI test configurations.

The intent of this discussion is to promote a facility design that can undergo hardness verification and periodic surveillance/reverification PCI testing with minimum mission downtime. It is not meant to require additional equipment or additional POEs for the sole purpose of PCI testability.

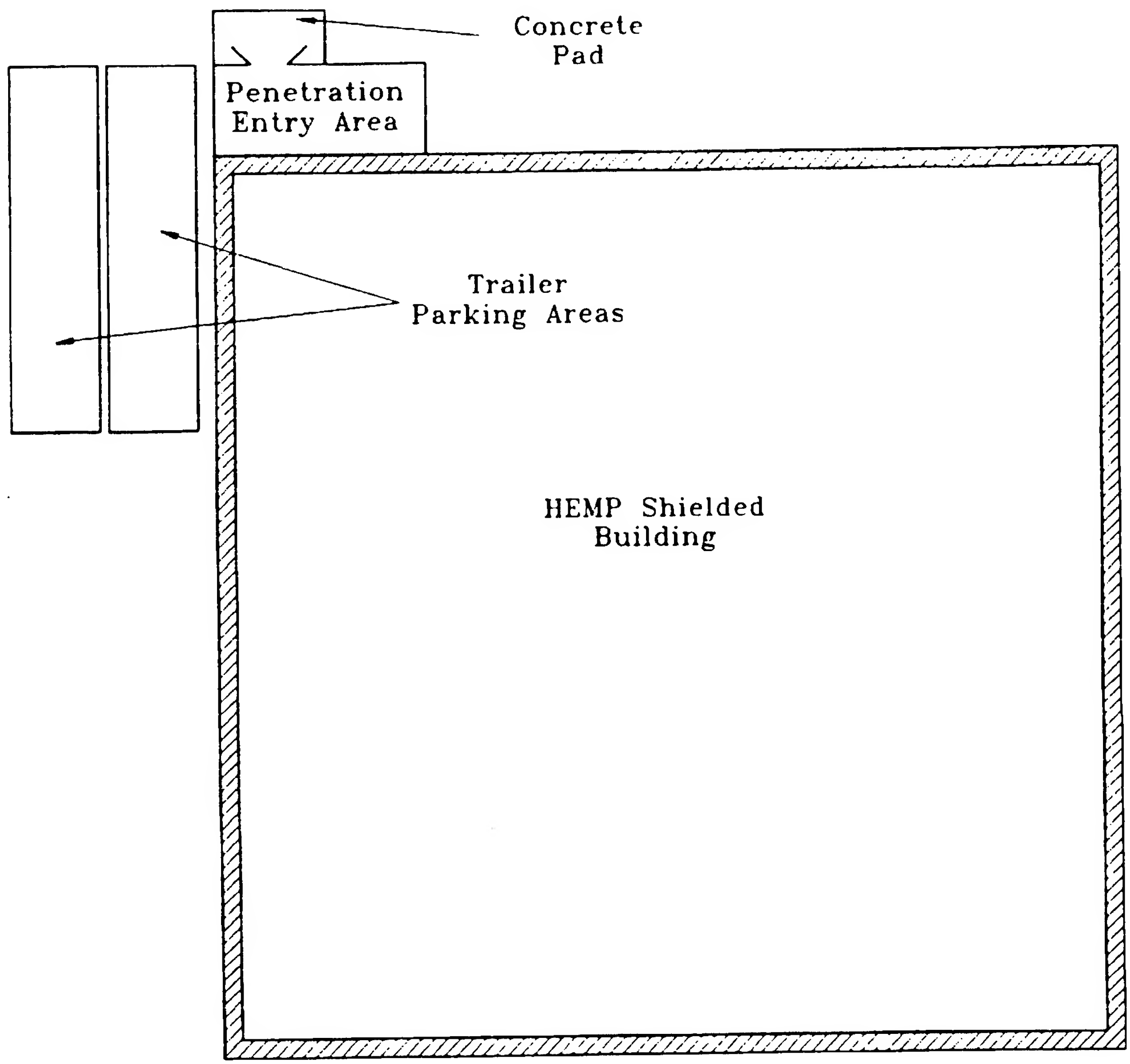
17.3.6.2 Electrical system design. The complete short, intermediate, and long pulse test sequence for the commercial power line POE will require six or more transitions between internal and utility-supplied sources. Therefore, it is strongly recommended that facilities HEMP-hardened in accordance with MIL-STD-188-125 be provided with a capability for paralleling site generators with the commercial power line. Additional discussion of the electrical power generation and distribution system design is found in section 7.

17.3.6.3 Penetration entry area design. MIL-STD-188-125 specifies that, as a design objective, piping and electrical POEs through the electromagnetic barrier should be concentrated in a single penetration entry area. The area should be located as far as practical from normal and emergency personnel and equipment accesses and ventilation POEs (see section 7). Electromagnetic interference and compatibility issues must be considered in the layout, since both power lines and low-level signal lines will be present (see section 12). Reliability and maintainability design requirements including accessibility and environmental conditioning are discussed in subsection 17.2.

PCI testing activities will be highly concentrated in the penetration entry area, because of the presence of a large fraction of electrical POE protective devices. Particular attention should therefore be given to PCI testability features of this area. Figure 174a illustrates the requirement for an outdoor parking area close to the PEA for at least two vans, which house PCI simulation sources and instrumentation. It may be necessary to locate up to two additional vans within approximately 50 m (164 ft) of the PEA door.

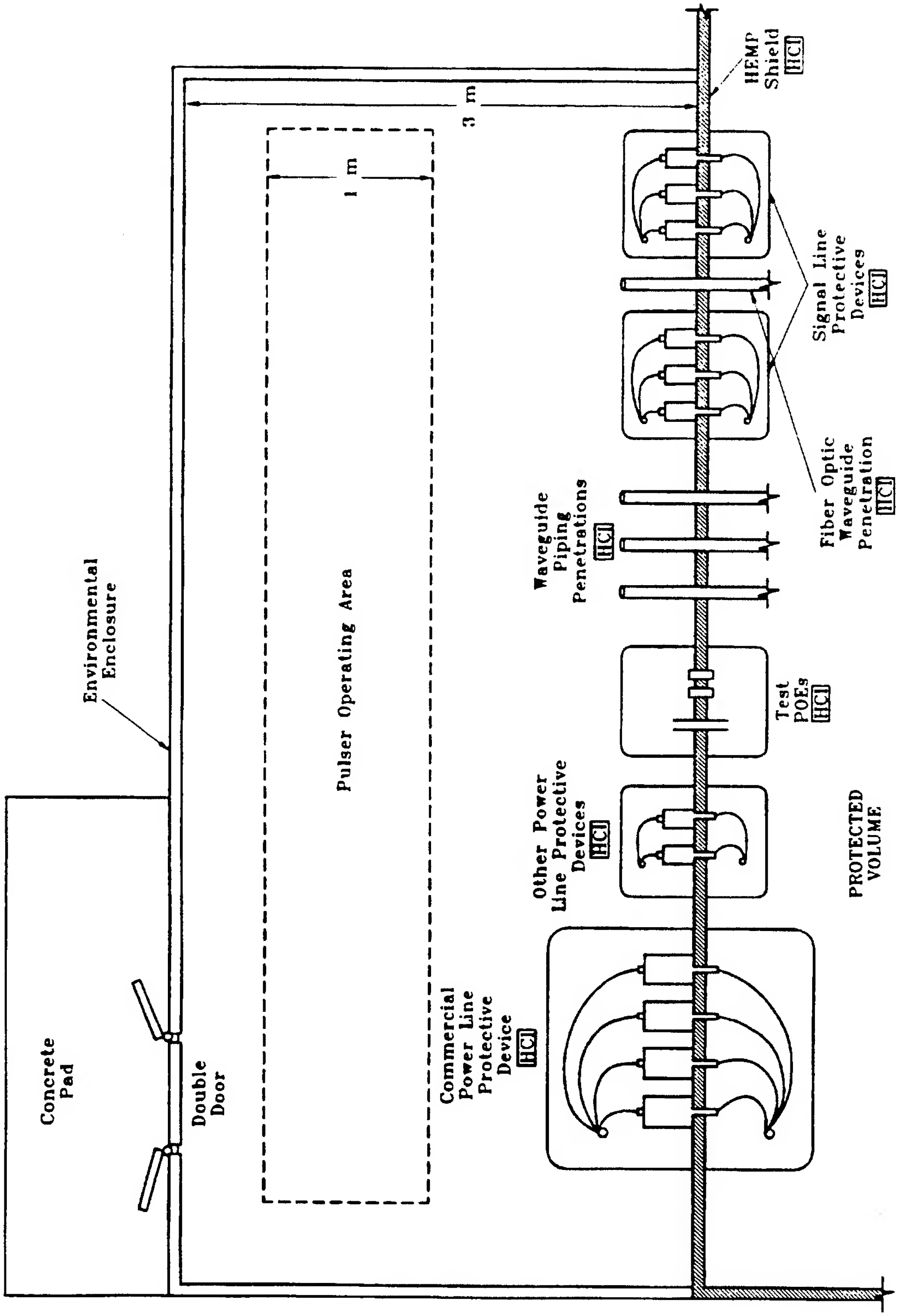
The PCI pulse delivery systems include large, heavy items of equipment that must be positioned in close proximity to each of the electrical POE protective devices. A double door, with an opening of at least 1.5 m (5 ft) wide by 2 m (6.6 ft) high, should be provided for moving the sources into the environmental enclosure. Ramps with less than 30-degree slopes should be supplied for any elevation changes. A 1-m (3.3-ft) corridor, extending the entire width of the space, should be reserved as the pulser operating area. The floor should be level, and conduits and pipes should be beneath the floor (or routed on the walls and ceiling) to avoid interfering with the movement of wheeled carts. The sketch in figure 174b highlights these design features.

The typical arrangement of POE protective devices shown by figure 174 is meant to illustrate three points. The commercial power line device, which contains very large



a. Typical site layout.

FIGURE 174. Typical penetration entry area.



b. Typical penetration entry area layout.

FIGURE 174. Typical penetration entry area (continued).

components, should be placed near the door. A central location should be chosen for the test POE panel, previously illustrated in figure 171. Finally, the physical separation between high-current power line devices and the signal line protection assemblies supports the electromagnetic compatibility design.

17.3.6.4 Filter/surge arrester assembly design. Figure 175 shows the external compartment of a typical, low-voltage (≤277 Vac to ground), low-current (≤200 A) filter/ESA assembly configured for normal operation and the circuit modifications that must be made to perform PCI testing. These changes include the following:

a. The normal circuit wiring has been broken at the connection posts and routed to the pulse delivery system.

b. Special test wiring from the pulse generator has been connected at the posts.

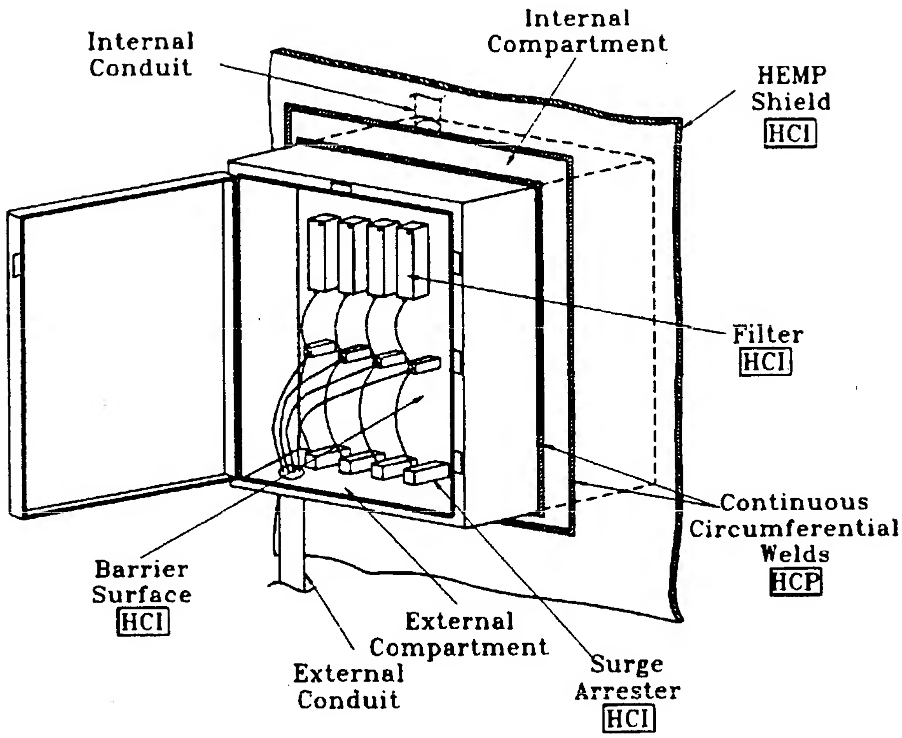
c. The external sensor has been installed on the conductor or conductors where measurements are to be taken.

d. Although not shown in figure 175, the internal current sensor has been installed on the appropriate conductor or conductors; dummy load resistors have also been installed for acceptance testing.

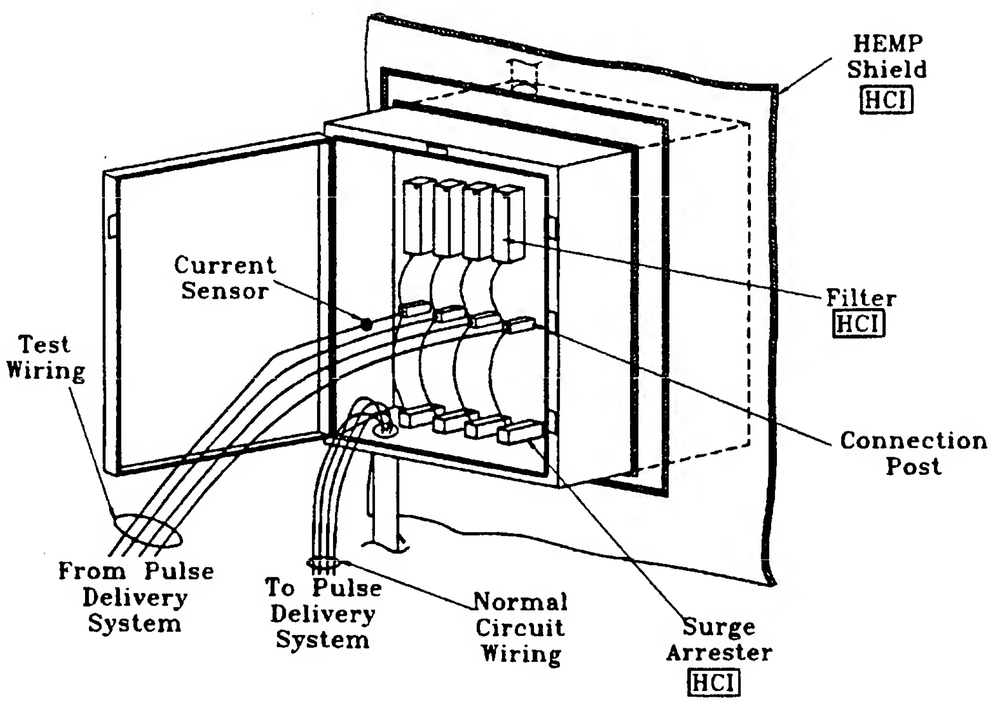
The assembly should be designed to accommodate these circuit changes.

The first two of these changes permit the transient pulse generator to be inserted in the penetrating electrical circuit between the incoming wiring and the input to the POE protective device. To facilitate reconnection, the length of the normal circuit wiring, from the open end of the external conduit to the connection posts, should be at least 50 cm (20 in). Since the filter/ESA assembly must generally be deenergized for this operation, appropriate disconnects must be provided.

MIL-STD-188-125 requires that the external current sensor be placed within 15 cm (6 in) of the connection post, and a similar restriction applies to the location of the internal current sensor. When the diameter of the conductor or wire bundle to be measured is less than 2 cm (0.8 in), the probe dimensions are approximately 8 cm x 8 cm x 3 cm (3.1 in x 3.1 in x 1.2 in). Instrumentation catalogs should be consulted to determine probe sizes for current measurements on larger conductors. The probe output will normally be connected to the input of a fiber optic transmitter, with dimensions of approximately 8 cm x 8 cm x 15 cm (3.1 in x 3.1 in x 5.9 in).



a. Normal operation.



b. Test configuration.

FIGURE 175. Filter/ESA assembly configuration for PCI testing.

Power filter/ESA assemblies operating at voltages greater than 480/277 Vac or currents in excess of 200 A are generally special designs. Although they must be topologically the same as the configuration shown in figure 175, they are likely to be physically different. The individual filters may be large devices, with dimensions of one meter or more and weights of hundreds of kilograms. Alternatively, multiple filters may be installed in parallel to obtain the required current-carrying capability. Very heavy gauge conductors are required, and rerouting of these is not feasible. PCI testability can be achieved for such cases by providing removable sections of bus bar or conductor at the input to the protective circuit. Figure 176 illustrates this concept, but the specific configuration must be tailored to the particular filter/ESA assembly design.

The spacing between the connection posts and the length of the removable section should be a minimum of 30 cm (1 ft). To perform PCI testing, the removable sections are removed. Pulse delivery system cables will then be connected at the posts. Lugs capable of accepting pulser cables with conductors up to 1.3 cm (0.5 in) in diameter should be provided for this purpose.

The couplers for use on rf coaxial penetrations are not designed as of the handbook publication date. A revision to this subsection will be made when the PCI testability features required for this class of penetrations are known.

PCI testing on filter/ESA assemblies of the imbedded design will normally be performed with the compartment access covers open. If the electromagnetic topology requires a cover to be closed during testing, however, space for four sensors and four fiber optic transmitters should be reserved within the enclosure. In such a case, one 2.5-cm (l-in) WBC and two N-type bulkhead feedthrough connectors should also be provided for transmission of test signals through the compartment wall.

17.3.7 Continuous wave immersion testability. The cw immersion test configuration is shown in figure 177, which has been taken from appendix C of MIL-STD-188-125. Swept or stepped frequency excitation is generated by the network analyzer, amplified to 100-1000 watts, and radiated from the antenna. Responses are recorded at various points inside and outside the electromagnetic barrier, and mission equipment operation is monitored for interference.

Ideally, there should be a clear area extending outward from the facility walls and externally placed equipment for at least 100 m (328 ft). Various types of antennas, possibly including a vertical monopole with height of approximately 30 m (98 ft) and a 200 m (656 ft) horizontal dipole (figure 178), will be used. During the test sequence, the antenna will be positioned at three or four different locations around the periphery of the building

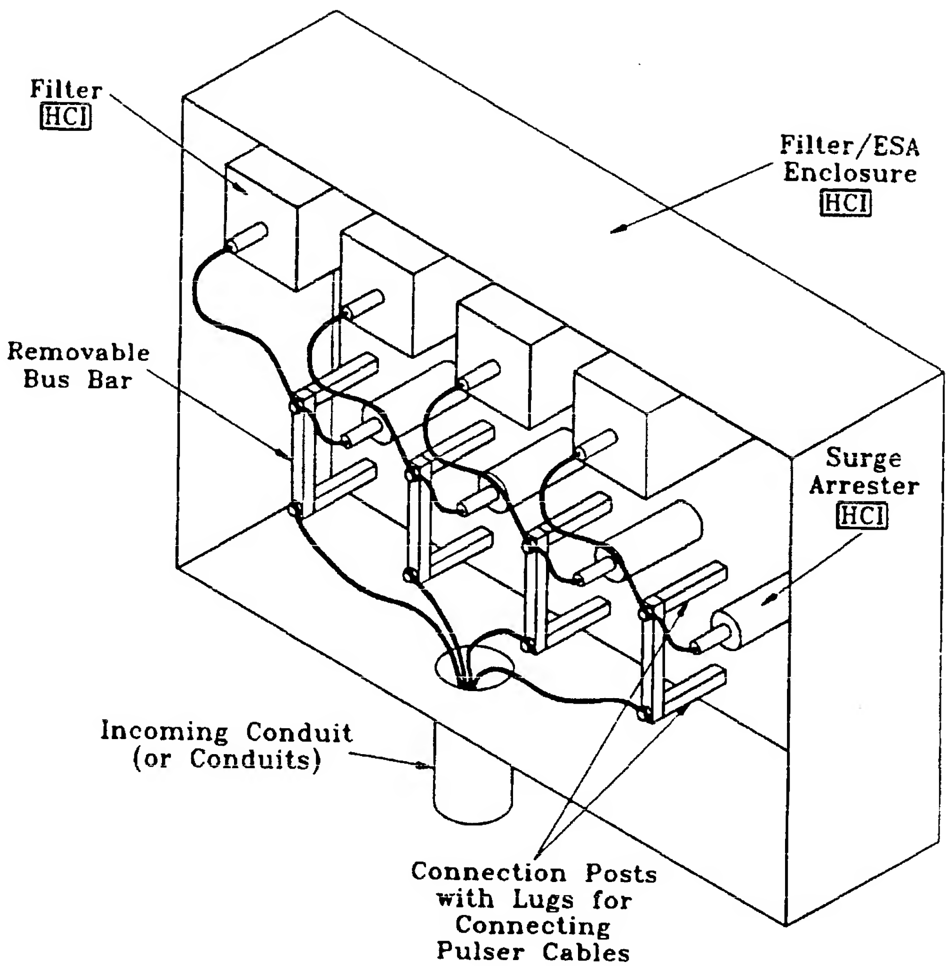


FIGURE 176. Possible high-voltage, high-current filter/ESA assembly configuration.

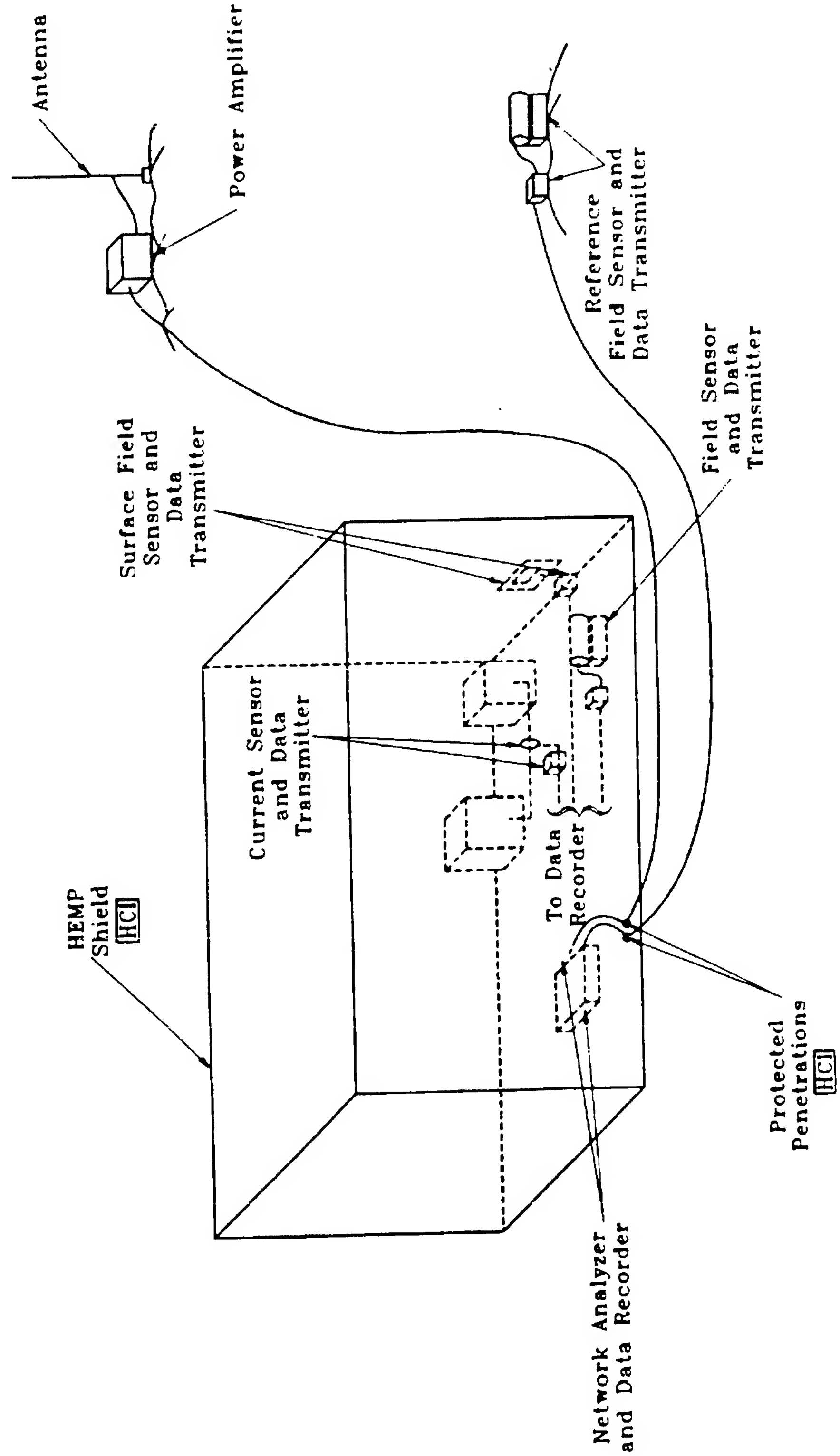


FIGURE 177. Continuous wave immersion test configuration.

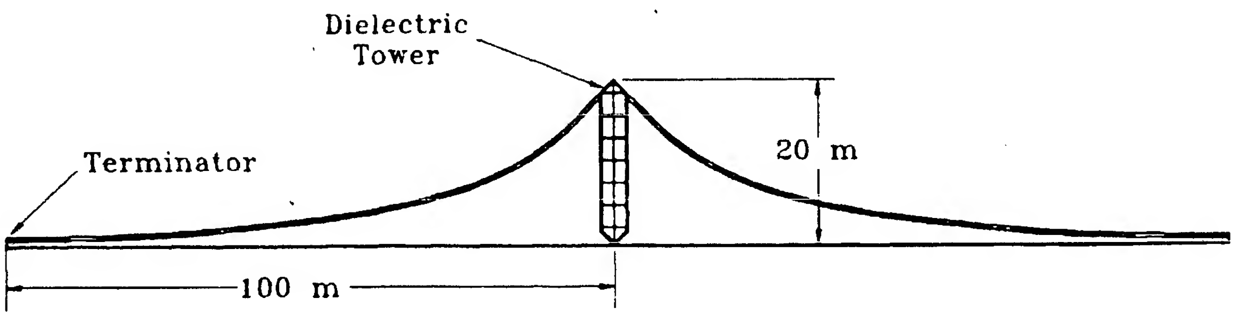


FIGURE 178. Horizontal dipole antenna.

at a ground distance of 30–60 m from the nearest shield wall. The purposes of the clear area are to permit antenna erection and to provide an unobstructed electromagnetic line of sight to the hardened facility.

The site location should be chosen to provide the clear area described above, if practical. When there are compelling operational or cost reasons to place the facility in close proximity to other structures, however, this clear area for cw immersion testability should not be the governing site selection criterion. Alternate cw excitation techniques are available.

When the HEMP-hardened systems occupy a small fraction of the space in a larger unshielded facility, illumination with radiating antennas is generally not feasible. The alternate cw excitation techniques will also be employed in this situation.

Interior equipment and cabling layouts are not constrained by cw immersion testability considerations in any way. Measurement point selection criteria are flexible, and the locations will be chosen during a pretest survey of the as-built installation.

The network analyzer and data recording equipment may either be inside the protected volume, as shown in figure 177, or in an instrumentation van parked near the building. Space requirements, if the instrumentation is inside, are modest; the equipment typically occupies one or two standard equipment racks.

Regardless of instrumentation placement, test signals must be transmitted through the electromagnetic barrier on fiber optic or coaxial cables. The same test POEs used in other test procedures—two 2.5 cm (1 in) diameter WBCs and four N-type bulkhead feedthrough connectors—will satisfy this requirement.

17.4 References.

17-1. "Military Standard - Reliability Modeling and Prediction," MIL-STD-756 (effective), Dept. of Defense, Washington, DC.

17-2. Blanchard, B. S., Logistics Engineering *and Management,* Prentice-Hall, Inc., Englewood Cliffs, NJ.

17-3. 'Military Standard - High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

17-4. "Defense Acquisition," DoD Directive 5000.1 (effective), Dept. of Defense, Washington, DC.

17-5. 'Defense Acquisition Management Policies and Procedures," DoD Instruction 5000.2 (effective), Dept. of Defense, Washington, DC.

17-6. 'Military Standard - Reliability Program for Systems and Equipment Develop ment and Production," MIL-STD-785 (effective), Dept. of Defense, Washington, DC.

17-7. "Military Handbook - Reliability Prediction of Electronic Equipment," MIL-HDBK-217 (effective), Dept. of Defense, Washington, DC.

17-8. 'Military Standard - Reliability Testing for Engineering Development, Qualification, and Production," MIL-STD-781 (effective), Dept. of Defense, Washington, DC.

17-9. 'Military Standard - Maintainability Program for Systems and Equipment," MIL-STD-470 (effective), Dept. of Defense, Washington, DC.

17-10. "Military Handbook - Maintainability Prediction," MIL-HDBK-472 (effective), Dept. of Defense, Washington, DC.

17-11. "Military Handbook - Maintainability Design Techniques; Metric," DoD-HDBK-791 (effective), Dept. of Defense, Washington, DC.

17-12. 'Military Standard - Maintainability Verification/Demonstration/ Evaluation," MIL-STD-471 (effective), Dept. of Defense, Washington, DC.

17-13. "Military Standard - Testability Program for Electronic Systems and Equipments," MIL-STD-2165 (effective), Dept. of Defense, Washington, DC.

17-14. "Military Standard - Definition of Terms for Reliability and Maintainability," MIL-STD-721 (effective), Dept. of Defense, Washington, DC.

17-15. 'Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Environment (U)," DoD-STD-2169 (effective), Dept. of Defense, Washington, DC (S).

17–16. Coburn, W. O., 'Evaluation of Large Loop Antennas for Hardness Surveillance," HDL-TM-89-13, U.S. Army Laboratory Command, Harry Diamond Laboratories, Adelphi, MD.

18. SAFETY AND HUMAN ENGINEERING

18.1 Basic principles.

18.1.1 Saf'ety and human engineering principles. Safety engineering is the application of scientific and engineering principles, criteria, and techniques to identify and eliminate hazards or to reduce the risks associated with hazards. Hazards lead to mishaps—events resulting in death, injury, or occupational illness to personnel and damage or loss of equipment or property.

Human engineering (or human factors engineering) involves the use of knowledge about human capabilities and limitations to design and operate equipment and facilities for optimal performance. Application of the concepts of this discipline ensures that hardware/software characteristics, human task requirements, and the work environment are compatible with the sensory, perceptual, mental, and physical attributes of the personnel, who will perform the operations and maintenance. Safety is an integral part of human engineering.

In order to achieve a safe and effective HEMP protection subsystem, the principles of human engineering must be incorporated into the design, construction, and operations and maintenance processes. Entryways must accommodate normal personnel traffic and must provide a means of rapid escape from the facility in case of fire or other emergency. Electrical installations must comply with safety standards, as well as functional requirements, and their operating, maintenance, and repair procedures must include applicable precautions. Designing for hardness maintenance and surveillance is another critically important element.

This section discusses safety and human engineering in design, construction, testing, operation, and maintenance of HEMP-hardened facilities. The text focuses on areas directly associated with the hardening features, including protective devices on safety-related POEs. Use of fire-retardant materials, electrically safe designs for power generating and distribution equipment, and similar aspects that apply to both hardened and unhardened systems are equally important, but they are not generally addressed here.

18.1.2 Safety and human engineering source documents. Origins of safety and human engineering requirements for systems and facilities are found in Department of Defense acquisition regulations including DoD Directive 5000.1, "Defense Acquisition" (reference 18–1) and DoD Instruction 5000.2, 'Defense Acquisition Management Policies and Procedures" (reference 18–2). These documents explicitly identify human factors per-

formance, along with mission functionality, survivability, reliability /maintainability, and other disciplines, as elements in the system engineering process.

Implementing information is published in various standardization documents and military department publications. Objectives and task descriptions for a formal safety and human engineering program are defined in MIL-STD-882 (reference 18–3) and MIL-H-46855 (reference 18–4). The program generally includes a planning phase, preliminary analyses to identify issues and options, trade studies to optimize solutions in terms of system performance and cost, detailed analyses of the selected approaches, reviews, and verification testing and evaluation. Acquisition management activities use the standards to choose and tailor tasks to meet the specific needs of their particular procurement, and the selected requirements are then included in the facility acquisition documents. Guidance for tailoring is provided in appendices to the standards.

Other useful reference materials include DoD-HDBK-763 (reference 18-5) and MIL-STD-1472 (reference 18-6). The handbook assists the safety and human factors engineers by explaining what should be done and when it should be accomplished and by describing the techniques for realization of the objectives. MIL-STD-1472 supplies the underlying anthropomorphic data and establishes engineering design criteria for particular human interfaces.

Although none of the cited documents directly address HEMP hardening, the information has significant impacts on the protection subsystem design and installation. Topics with specific applicability include the following:

a. General workspace environmental requirements, including ventilation and lighting

b. Force limitations on the operation of shielded doors

c. Design requirements for controls and displays

d. Requirements for access covers and fasteners and other aspects of designing for maintainability

e. Labeling

f. Hazards avoidance

In addition to references described above, other military standardization documents and various DoD-adopted commercial standards address the subjects of electrical, construction, and fire safety. These references will be cited when applicable in later parts of the section.

18.2 MIL-STD-188-125 requirements.

5.1.10 Safety and human engineering. Safety and human engineering criteria, principles, and practices shall be applied in the design, selection, and placement of HEMP protection subsystem elements. Entryways shall be designed to accommodate expected traffic and shield doors shall operate simply with operating forces within limits imposed by MIL-STD-1472. Inspection covers shall be designed for safety and ease of removal and proper reinstallation. Electrical POE protective devices shall provide fail-safe features, such as capacitor discharge resistors, for protection of personnel during installation, operation, maintenance, and repair.

MIL-STD-188-125 (reference 18-7) establishes these requirements to ensure that human factors will be reflected in the HEMP hardening design and to highlight the protective features that are most strongly" impacted by such considerations. Safety and human engineering criteria and principles apply to all aspects of design, installation, test, operation, maintenance, and surveillance of the HEMP protection subsystem. Safety for construction workers, test team personnel, operators, and maintainers is a matter of paramount importance and must be a primary concern in development of the design. These provisions, in conjunction with other requirements throughout the standard, are intended to provide hardening that can be maintained at a high level of performance in the environment of an operational facility.

There is one additional underlying (rather than explicit) goal in the standard in which human factors play a critical role. The hardening is to be designed and implemented in a manner that minimizes the possibility of compromise by the inadvertent actions of operators and maintenance personnel, who may not be "experts" in HEMP survivability phenomenology and practices.

18.3 Applications.

18.3.1 General design guidance. Safety and human engineering programs in accordance with MIL-STD-882 and MIL-H-46855 are recommended during the design phase for new construction and major retrofits to MIL-STD-188-125 facilities, and the HEMP protection should be included in these programs. Since the application of these disciplines to the hardening design is relatively straightforward, rather simple requirements may be imposed on the HEMP designer. The following tasks are suggested:

a. MIL-STD-882, task 100 – establishes the requirement for a safety program

b. MIL-STD-882, task 210- analyzes the system to identify hazards and to evaluate compliance with safety standards

c. MIL-H-46855, paragraph 3.2.2.4 – evaluates the system specification for conformance to human engineering criteria

d. MIL-H-46855, paragraph 3.2.3.1- defines safety and human engineering demonstration requirements; these requirements should be included in the quality assurance provisions of the facility construction specifications

The construction specifications must explicitly reflect safety/human engineering performance and demonstration requirements that result from these HEMP design activities. Formal programs in accordance with the military safety and human engineering standardization documents are generally not needed for the HEMP protection subsystem during the construction phase; Government enforcement of both general and specific provisions in the specification and insistence on good commercial safety practices of the building industry will suffice. If formal safety and human engineering program requirements are imposed for other reasons, however, the HEMP protection subsystem should also be covered by them.

One of the major human engineering criteria is serviceability of the design. Past experience has shown that costly and time-consuming maintenance can be avoided when reliability, maintainability, and testability are high priority design considerations, The shield and POE protective devices must be accessible for inspections and effectiveness measurements. Sufficient clearances must also be provided for personnel and equipment to remove and replace defective HCIs and to perform other HEMP protection subsystem repairs when needed. Requirements and guidelines in designing for maintainability and testability are addressed in greater detail in section 17.

General safety requirements applicable to the design and construction of buildings, including HEMP-hardened facilities, are promulgated as codes and standards that are listed in MIL-BUL-36 (reference 18–8). Those of particular interest because of impacts on the HEMP hardening include ANSI/NFPA 101, "Code for Safety to Life from Fire in Buildings and Structures" (reference 18–9), and the ANSI/IEEE C2, "National Electrical Safety Code" (reference 18–10). Unless specific exemptions are provided, military construction projects are generally specified to conform to the requirements in these documents.

All safety-related barrier penetrations must comply with both safety regulations and MIL-STD-188-125 requirements. To accomplish this, the HEMP designer should coordinate closely with the architect on entryway configurations and with individuals responsible for the fire extinguishing subsystems, fire alarm circuits, and the grounding and electrical safety installation.

As the final item of general guidance, the HEMP designer is reminded to consider habitability along with operational and safety requirements. Protected POEs for commercial radio and television reception are probably needed, for example, when there are break rooms or living quarters inside the electromagnetic barrier. Unless properly hardened penetrations for such amenities are installed as part of the facility development, the staff may provide them later, in a manner which compromises the HEMP survivability.

The remainder of this section discusses specific safety and human engineering aspects of MIL-STD-188-125 HEMP shields and POE protective devices.

18.3.2 Personnel entryway and shielded door design.

18.3.2.1 Number and types of entryways. Because of difficulties experienced in maintaining the required shielding effectiveness of rf shielded doors, minimizing the number of entryways and shielded doors is highly desirable. The principal considerations in making this determination, however, must be to accommodate normal personnel traffic at the facility and to provide safe escape in the event of emergencies. MIL-STD-188-125 therefore establishes a design objective to limit the number of entryways to the minimum requirement of ANSI/NFPA 101, based upon building layout and occupancy. When particular hazardous operations or floor plan constraints on movement dictate a greater quantity of entryways, safety should be the overriding factor.

For the same reason, a waveguide-below-cutoff design is preferred for routinely used entryways due to the partial fail-safe attributes of this configuration and the reduced shielding requirements for the doors. Waveguide dimensional constraints, along with the sequencing time for the interlocked doors, will generally limit the entry rate to 20-30 persons per minute. If this rate is insufficient, a large area vestibule design should be chosen.

Small vestibules are usually selected for emergency-only exits for reasons of cost.

18.3.2.2 Entryway lighting and ventilation. Entryways are personnel spaces. They must satisfy environmental requirements for "passageways" from MIL-STD-1472 and from other specified codes and standards. Emergency lighting specifications of MIL-STD-1472 and ANSI/NFPA 101, including requirements for self-contained power sources and auto matic switching, also apply since these entryways/exits are the escape routes.

Entryway shield penetrations will be required for both lighting and ventilation, and the hardening at these POEs must provide the electromagnetic performance specified by

MIL-STD-188-125. Protective device designs for these applications are also discussed in handbook sections 9, 10, and 12.

18.3.2.3 Shielded doors. The functions of shielded doors are to provide for the free flow of personnel traffic while preserving the integrity of the electromagnetic barrier under normal operating conditions and to permit safe escape during emergencies. The doors are the only elements in the HEMP protection subsystem that are 'operated" by site staff members on a daily basis.

The principal impacts of safety and human engineering on the shielded door selection process relate to door maintainability and to specifications for the door hardware and operating parameters. MIL-STD-1472 and ANSI/NFPA 101 both contain maximum operating force limitations, which are explicitly applicable when the door is employed as an emergency exit; it is suggested that the same force constraints be specified for normal operation. These references also establish related escape safety criteria including direction of the application of force, direction of swing (for swinging doors), minimum dimensions of the unobstructed opening, and maximum operating time.

If the HEMP shielded doors are power-operated or power-assisted, they should go to a safe-escape condition upon complete loss of power (including any backup uninterruptible power source). The doors should fail in a closed, but unlocked, state when manual mode operating parameters satisfy the emergency exit requirements. Otherwise, the doors should fail in the open position.

These safety requirements should appear explicitly in the HEMP protection subsystem section of the construction specifications. Quality assurance provisions requiring a demonstration of compliance with the safety criteria, as well as electromagnetic and mechanical tests to demonstrate other aspects of acceptable performance, should also be included.

When doors are designated as emergency exits and are not intended for routine entry and egress, misuse in nonemergency situations can be discouraged by not installing external hardware. However, a means by which fire fighters and other special response teams can enter from the outside should be available. For example, the handle for emergency use could be stored in a glass case, which is mounted next to the door.

Door interlocks and alarms are also provided to assist site personnel in proper use of entryways. A discussion of safety and human factors considerations for these circuits will be presented in the next subsection. It is simply noted here that this arrangement is sufficiently unusual to merit posted operating instructions.

18.3.2.4 Shielded door interlocks and alarms. Entryway interlocks and alarms are intended to assist personnel entering or leaving the protected volume to operate doors correctly, without compromising the effectiveness of the HEMP barrier. The interlocks provide signals that control the sequencing, ensuring that at least one door of each pair is shut at all times during normal conditions. The alarms indicate that an improper operation has been performed and that the HEMP hardness may be or has been violated.

A complete list of interlock and alarm circuit features is suggested in section 9. At this point in the text, only those functions directly related to safety are restated:

a. Door interlocks should be automatically disabled by fire and other emergency condition alarms, in order not to impede escape routes.

b. Override-on-demand should be provided, so that a door can be operated if the companion door is inadvertently left open and if its position sensor or the associated logic circuit malfunctions.

18.3.3 Equipment access POE cover design. Electromagnetic closure covers for equipment access POEs, when required, are to be designed for safety and ease of removal and proper reinstallation. Equipment in the vicinity of the access port should be located to avoid interference during opening and closing of the cover, and interior and exterior building finish work should be designed so that extensive disassembly is not required as part of the cover removal procedure. Sharp edges and corners that might pose a personnel hazard should be avoided on the closure plate and the fixed mounting surfaces. When the electromagnetic cover is removed, the clear opening must be of adequate size for the operations to be performed.

Since equipment accesses are permitted only when the hardware is too large and heavy to be moved through a personnel entryway, weight of the cover will generally exceed the human lifting constraints of MIL-STD-1472. In these instances, the preferred cover design is a hinged door. The cover should be sufficiently rigid and the hinges of adequate strength that the door is self-supporting in any position. There should also be positive latching in the open position to prevent accidental closure.

A completely removable cover, such as the design previously illustrated in section 9, can be used when a hinged door is not practical. Permanent fittings for handling by crane or forklift should be installed. Alignment pins on the fixed surface to engage holes in the cover should be provided as an aid in positioning during the reinstallation sequence.

The cover must be continuously seam welded in place if anticipated usage is less than once per three years. To remove it, the weld seams are cut away with a cutting torch. The cover is then rewelded when the work is finished.

A mechanically fastened cover may be provided when the anticipated usage is more frequent than once per three years. Fasteners should be rugged and of a standard design, operable with standard tools. Captive fasteners should be used whenever possible. Sheet metal screws are not recommended for shielding applications.

The rf gasket employed with a mechanically fastened cover should be easily positioned, securely held in place, and protected from damage during opening and closure. The preferred designs are preformed gaskets that mount on the studs or alignment pins and "O-ring" type gaskets captively held in a narrow groove. Gaskets that must be affixed with a conductive adhesive are not recommended, and gaskets that must be spot welded in place should not be used.

Covers should be labeled with the nomenclature of items accessed through the port. Removal and reinstallation instructions, including specific torquing requirements for the fasteners, should be prominently displayed on the cover unless the procedures are obvious from the configuration. HCI identification markings are also required (see section 19).

18.3.4 Filter/ESA assembly designs. MIL-STD-188-125 specifies that each electrical conductor penetrating the electromagnetic barrier must be HEMP protected with an electronic surge arrester and additional linear and nonlinear devices as needed to meet the transient suppression/attenuation criteria. Filters, consisting of capacitor-inductor passive networks, and spark gaps or MOVs are generally used in this application (see section 12).

Filter/ESA assemblies must, of course, comply with electrical installation and safety codes and standards specified by the contract. The principal safety and human engineering issues involved in the design and selection of these components are discussed in the subsections below.

18.3.4.1 Filter and ESA selection. Filters operating at 600 V and lower potentials and qualified to ANSI/UL 1283 (reference 18-11) or MIL-F-15733 (reference 18-12) can generally be considered to be satisfactory in terms of electrical safety. A number of qualifications to this statement need to be made, however, and they are identified in the following list:

a. The Underwriters Laboratory standard contains a requirement for discharge of capacitively stored energy via a bleeder resistor or other means; MIL-F-15733 does not

include such a requirement. When the latter is specified, the designer should consider addressing this subject in the facility specification articles on filters.

b. MIL-F-15733 is somewhat more comprehensive than ANSI/UL 1283 in terms of environmental factors. In either case, the designer needs to verify compatibility with the conditions which will exist at the particular facility.

c. The style sheets that supplement MIL-F-15733 take precedence over the MIL-F-15733 basic document and may, therefore, modify or eliminate requirements in the specification.

d. Neither document addresses reactive leakage current (for filters of the type used in HEMP hardening) or harmonic generation; these topics are addressed in section 12. (Furthermore, neither document guarantees compliance with the transient isolation requirement of MIL-STD-188-125.)

e. Most commercially offered filters are "designed to," rather than 'qualified to," these standards; the difference is the extent of the testing program. If qualification is not required, safety compliance demonstrations should be specified in the facility acquisition documents.

Maintenance of good grounding connections for filters and surge arresters is particularly important, both as a safety issue and for reasons of POE protective device performance. Filters and ESAs must be securely grounded to the metal enclosure. The enclosure is then electrically bonded to the HEMP shield via circumferential welds, and the shield is connected to the earth electrode subsystem. Handbook section 13 discusses grounding and bonding requirements.

Filters at voltages in excess of 600 V experience high and continuous electrical stresses, and components are subject to damage and failure due to partial discharge. Frequent failures have occurred in the past and, in some instances, the events have been explosive. Work to solve this problem is in progress, but is incomplete as of the publication date of this handbook. Therefore, the designer is strongly encouraged to make the commercial feeder and other power penetrations into the protected volume at 480/277 Vac and below whenever possible. If a POE at higher voltage cannot be avoided, acquisition of the filter/ESA assembly must be handled as a developmental program.

Safety considerations in ESA selection are relatively straightforward. First, the device must be rated for continuous operation at the peak line voltage of the circuit on which it will be installed. Second, the ESA must be designed to "turn off" after passage of the transient with operating voltage still applied to the circuit or provisions to disconnect

or deenergize the source must be made. Manufacturers' applications engineers should be consulted and device data sheets should be reviewed to ensure that the chosen ESA is appropriate for the intended use. Operating and extinguishing characteristics should also be verified by testing.

Some spark gaps employ a small radioactive source to preionize the gas contained in the housing. The manufacturers have been consulted, and they indicate that no special handling is required because of the type and amount of radioactive material employed. Nevertheless, current regulations should be reviewed when disposing of such devices.

18.3.4.2 Filter/ESA enclosure. Many HEMP filters and ESAs are used on power line penetrations and have exposed terminals, operating at potentially dangerous voltages. Good electrical safety practices, therefore, dictate that the components be installed in grounded metallic enclosures to avoid personnel hazards. The housing also serves to protect the filters and surge arresters from dirt, spray, and other detrimental environments.

Periodic access into the interior of the enclosure will be required for inspection, testing, and repairs. The anticipated frequency of access is one to three entries per year. Design of the enclosure and the surrounding area must provide adequate space for removal and replacement of the filters and surge arresters and for locating the simulation sources and instrumentation required for PCI testing. This topic is discussed in additional detail in the handbook sections on filter/ESA design, reliability, maintainability, and testability (see sections 12 and 17).

The "imbedded" configuration, illustrated by figure 179, is required for MIL-STD-188-125 filter/ESA assemblies. In this arrangement, neither the external compartment nor the interior compartment is required to be shielded unless such shielding is specified as a special protective measure. Differences between an rf shielded compartment and an unshielded one are principally as follows:

a. Seams in the basic housing for a shielded compartment will be continuously welded, while those of an unshielded compartment may be spot welded, riveted, or bolted.

b. An RFI gasket or a combination RFI and environmental gasket provides electrical continuity between the cover and box of a shielded compartment; only an environmental gasket is generally used for an unshielded compartment.

c. A larger number of more closely spaced fasteners may be required to secure the cover of a shielded compartment.

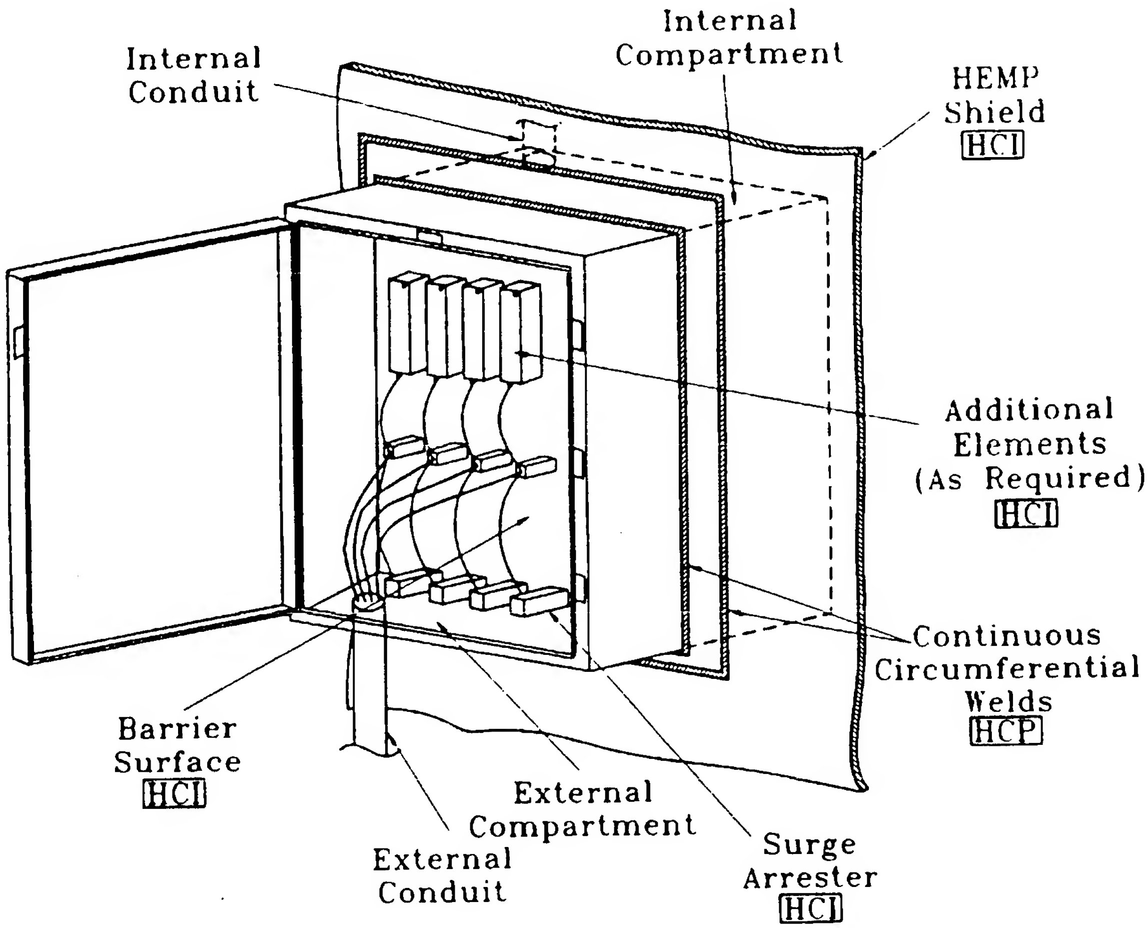


FIGURE 179. "Imbedded" electrical POE protective device.

Designers are cautioned that the standard enclosures available from most filter manufacturers at the time of handbook publication are not the imbedded configuration. Fabrication by the construction contractor or a special order will be required.

The access covers for a few filter/ESA enclosures, such as those protecting the commercial power feeder, may be large and comparable in size to the closure plates described for equipment accesses. In such cases, when the cover weight exceeds human lifting constraints, the handling design guidance provided in 18.3.3 is applicable.

More frequently, the covers are small and within the lifting capacity of a single individual. The design concepts are the same, nevertheless. A hinged cover is preferred, and a

completely removable cover with handles and fasteners in accordance with MIL-STD-1472 is the alternate choice. When a hinged cover is provided, a ground strap should be installed so that electrical bonding to the enclosure does not rely on incidental contact through the hinges.

HEMP filter/ESA enclosures should be labeled with nomenclature data, identification of the protected circuit, HCI tags, and appropriate electrical safety warnings. These labels should be placed on covers of both the exterior and interior compartments.

It is strongly recommended that all filter/ESA enclosures be installed in a temperature and humidity-controlled environment to minimize condensation and corrosion. In any case, however, the enclosure must be designed in accordance with ANSI/NEMA 250 (reference 18–13) for the environment in which it will be placed.

18.3.5 Shielded pull boxes and other small enclosures. In addition to the large equipment access POEs in the primary barrier and filter/ESA enclosures, other accesses with rf closure requirements may be employed in the HEMP protection system. Examples include pull box covers in shielded conduit runs and panels in equipment-level shields. When practical, such covers should be seam welded in place. When welding is not practical, rf-gasketed seals should be provided. In all cases, the access openings and cover designs should comply with the requirements of MIL-STD-1472.

18.3.6 Construction safety. Special hazards may be encountered during a construction program because of the need to move large and heavy items and because safety system installations—such as the electrical grounding system—may be incomplete. Furthermore, a broad spectrum of workers are engaged in relatively independent tasks at locations throughout the site. Although the safety issues and required precautions are not particularly unique to fabrication of the HEMP protection subsystem, several of the potential dangers merit discussion in this handbook.

Barrier assembly requires the use of electric arc welders to perform seam welds between adjacent shield plates and to install the POE protective devices, where the metal objects to be joined may not yet be permanently bonded to the earth electrodes. This condition may cause a hazard to exist when the 'hot" lead of the welder is touched to the shield. The welding equipment ground terminal should therefore be connected to the particular plate on which work is being performed. Unless the equipment ground and the metal objects are electrically bonded to a common ground point through low resistance conductors, the high currents used in this process can return at inadvertent contact points—including through the operator or other workers.

Another potentially hazardous condition occurs when welding galvanized steel. This operation produces toxic fumes, and it must be performed only in well-ventilated spaces with adequate protection for the welder and other individuals in the area.

Because of the high welding voltages, currents, and temperatures and the chemical reactions which can be promoted under these conditions, strict adherence to welding safety precautions is essential. ANSI/AWS 249.1 (reference 18–14), a DoD-adopted industrial standard on welding safety from the American National Standards Institute and the American Welding Society (AWS), should be consulted and followed.

HEMP protection filters also require special handling during the construction phase. These devices employ large capacitors to achieve conducted transient isolation, and the capacitors may acquire an electrical charge during attenuation measurements and circuit functional tests. When the filters are energized, circuit breakers and enclosures should be tagged with high voltage warning signs. Capacitors must be discharged and the filter input and output connectors should be securely grounded after the power has been removed.

HCIs also require physical and,environmental protection during transport and storage and after installation. This is particularly true for the electromagnetic seals on rf shielded doors.

18.3.7 Safety during acceptance and verification testing. Testing represents another activity during which special attention to safety is dictated. All test plans should include a careful evaluation of potential hazards to personnel and property, and precautions for eliminating or minimizing risks should be noted in bold-faced characters at the appropriate steps in the procedures. The “two-man” rule should be specified for all activities involving potentially hazardous conditions. Instructions to be followed in the event of an accident, including emergency treatment and arranging transportation to the nearest hospital, should be provided. Obviously, all test safety precautions should be followed when the experiments are performed.

The PCI test requirements of MIL-STD-188-125 employ pulse generators operating at voltages high enough to be lethal, and these procedures must therefore be executed with extreme care. The high voltage sources, injection points, and exposed measurement points should be roped off and clearly marked with warning signs before testing begins. Visual and audible signals should be provided to alert all personnel in the vicinity whenever the pulse generators are capable of being triggered. All applicable safety requirements of the military department and local safety organizations should also be observed.

Sources of normal operating voltages and currents at the test points to be injected and those to be monitored will generally be disconnected during acceptance testing. However, verification tests are conducted with the facility powered and performing actual or simulated mission functions. Equipment should be deenergized for installation and removal of sensors and other special test connections, unless the safety of working on live circuits can be unequivocally shown. Extreme care must also be exercised to avoid inadvertent grounding of live conductors and transmission of dangerous potentials via the instrumentation cabling.

In summary, test safety involves the identification of potential hazards in the planning process, establishment of procedures which avoid risks, and strict adherence to these procedures during test execution.

18.3.8 Operations and maintenance safety. The key elements to an effective safety program during the operations and support phase of the facility lifetime are very similar to those just described for a test program. Specifically, they include the following activities:

a. Identification of potential system hazards during the design phase and development of safe designs

b. Identification of potential hazards during the preparation of operating instructions and HM/HS procedures and inclusion of adequate safety precautions in the HEMP protection subsystem manuals

c. Strict adherence to safety requirements by the operations and maintenance staff

Operators and maintainers have obligations beyond that of simply following the written procedures. If a deficiency in the procedures is found, it is their responsibility to initiate the sequence for revising the manual. Furthermore, when actions not covered by the procedures are required, a hazards assessment must be made by facility at the local level.

18.4 References.

18-1. 'Defense Acquisition," DoD Directive 5000.1 (effective), Dept. of Defense, Washington, DC.

18-2. "Defense Acquisition Management Policies and Procedures," DoD Instruction 5000.2 (effective), Dept. of Defense, Washington, DC.

18-3. 'Military Standard - System Safety Program Requirements," MIL-STD-882 (effective), Dept. of Defense, Washington, DC.

18-4. "Military Specification – Human Engineering Requirements for Military Systems, Equipment and Facilities," MIL-H-46855 (effective), Dept. of Defense, Washington, DC.

18-5. "Military Handbook - Human Engineering Procedures Guide," DoD-HDBK-763 (effective), Dept. of Defense, Washington, DC.

18-6. "Military Standard – Human Engineering Design Criteria for Military Systems, Equipment and Facilities," MIL-STD-1472 (effective), Dept. of Defense, Washington, DC.

18-7. "Military Standard - High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

18-8. "Military Bulletin – U.S. Building Codes and Standards; an Overview," MIL-BUL-36 (effective), Dept. of Defense, Washington, DC.

18-9. "Code for Safety to Life from Fire in Buildings and Structures, " ANSI/NFPA 101, American National Standards Institute, New York, NY.

18-10. 'National Electrical Safety Code," ANSI/IEEE C2, American National Standards Institute, New York, NY.

18-11. "UL Standard for Safety - Electromagnetic Interference Filters," ANSI/UL 1283, American National Standards Institute, New York, NY.

18-12. 'Military Specification – Filters and Capacitors, Radio Frequency Interference, General Specification For," MIL-F-15733 (effective), Dept. of Defense, Washington, DC.

18-13. "Enclosures for Electrical Equipment," ANSI/NEMA 250, American National Standards Institute, New York, NY.

18-14. "Safety in Welding and Cutting," ANSI/AWS Z49.1, American National Standards Institute, New York, NY.

19. HEMP CONFIGURATION MANAGEMENT

19.1 Basic principles.

19.1.1 Configuration management principles. The discipline of configuration management employs technical and administrative direction and surveillance to accomplish the following objectives:

a. To identify, verify, and document the functional and physical characteristics of the managed configuration item

b. To control changes to the configuration item and its documentation

c. To define and control interfaces between configuration items

d. To provide configuration traceability and accounting

Configuration management begins in the earliest stage of the life cycle and continues until the configuration item is deactivated and discarded. It permits the orderly development of the managed system, equipment, or software; establishes a planned process for changes; and ensures continuing compatibility and interoperability between configuration items. Effective configuration management procedures thus provide the means for preserving functional integrity.

Principal activities in a configuration management program include initial development of configuration baselines, baseline documentation, configuration change control, and configuration audits. There are three baselines—functional, allocated (interface), and product (functional and physical) —which will be sequentially established as the configuration item design evolves. These baselines are identified in specifications, drawings, manuals, and other technical documentation. These documents serve as the basis for the change control process.

Proposed changes are reviewed to identify impacts on the functional and physical characteristics of the managed hardware or software. Presuming that these impacts are consistent with the operational requirements, the configuration manager recommends approval of the change to the appropriate authority. Implementation of the change includes both modifications of the configuration item and revisions to the documentation. The original baselines plus all approved and implemented changes then constitute the current or approved configuration identification.

A configuration audit is performed to verify that the as-installed configuration item and its configuration identification agree, are complete and accurate, and satisfy program requirements.

19.1.2 HEMP configuration management. HEMP configuration management is simply the configuration management program for the HEMP protect ion subsystem to preserve the operationally required mission survivability. It begins in the facility planning, programming, and budgeting phase, when the HEMP survivability requirements are defined and hardening and maintenance concepts are formulated. The initial baselines are established during building design and documented in the construction drawings and specifications. Change control is implemented in the construction phase and continues through the end of facility life.

Changes to the HEMP protection subsystem of a ground-based C^4I facility will occur for a wide variety of reasons. Mission and mission-essential equipment requirements and threat scenarios are continuously reassessed, and site modifications are implemented as necessary. Hardware is also replaced as improved models become available and older units become unsupportable. Many of these changes will also require modifications to the electrom agnetic barrier or the special protective measures.

Some modification affect the HEMP protection subsystem in obvious ways; examples include the following cases:

a. Barrier topology changes and changes in shield materials, installation details, or fabrication methods

b. Addition (and deletion) of POEs through the primary electromagnetic barrier, a special protective barrier, or an entryway shield

c. Replacement and modification of existing POE protective devices or HEMP protection conduits

d. Changes to MEE hardened with SPMs, since these measures must be tailored to the particular installation

e. Replacement or other changes to existing special protective devices

Such site modifications involve HCIs, and they must be designed and implemented in accordance with applicable provisions of MIL-STD-188-125 (reference 19-1). They must also comply with the MIL-STD-188-125 hardness quality assurance and acceptance test requirements during the implementation program and verification test requirements following completion.

The hardness impacts of other site modifications may be more subtle. Any change to MEE enclosed within the electromagnetic barrier can alter the internal HEMP coupling, residual transient propagation path, or equipment vulnerability threshold. Because the low-risk approach constrains the residual internal stresses to very small-amplitude transients, however, such a change is considered to be minor when the shield and penetration protective devices are unaffected.

Any proposed change to MEE hardened with special protective measures, nonessential equipment interconnected with such MEE, and special protective HCIs must be carefully assessed for hardness impacts. Similarly, the late-time HEMP response and protection must be reassessed whenever a new intersite conductor is to be introduced, even if that conductor will not penetrate the barrier.

Verification testing is required after any HEMP protection subsystem modification that has a potential hardness impact. For a major retrofit, the verification should be done as soon as practical after completion of the project. When the change is relatively minor, the testing may be deferred until the next scheduled hardness surveillance test.

Because seemingly minor changes to the HEMP protection subsystem can have significant impacts on site hardness, configuration management is a critical element in the HEMP subsystem life cycle. This handbook section outlines recommended guidelines and practices for an effective HEMP configuration management program.

19.1.3 Configuration management source documents. Basic DoD policies and requirements for configuration management on military systems and equipment are promulgated in defense acquisition directives and instructions (references 19-2 and 19-3). These documents direct acquisition program managers to conduct appropriate configuration management activities during the development of the hardware or software. The requirements continue to apply during the deployment phase and, when the system or equipment is transferred to the user and service supporting command, responsibility for configuration control also transfers to these organizations.

Guidance for implementing configuration management is amplified in military standards. MIL-STD-973, "Configuration Management" (reference 19-4), is the most comprehensive of these standardization documents. It provides definitions of configuration management terms, describes elements of the program, and establishes uniform practices. The standard also identifies additional reference documents of potential value to the manager.

An important provision in MIL-STD-973 is the requirement to tailor configuration management procedures to be consistent with the complexity, criticality, quantity, and intended use of the managed configuration item. The level of detail and control of the HEMP configuration management program must therefore be chosen to be sufficient for maintaining facility hardness, without requiring excessive manpower or costs for execution. HEMP configuration management should be integrated with the overall site configuration management process by explicitly including hardness in the control board charter and designating the HEMP program manager as a board member.

19.2 MIL-STD-188-125 requirements.

> 5.1.19 Configuration management. A hardness configuration management program shall be implemented during design and construction of the HEMP protection subsystem. Hardness critical items and hardness critical processes shall be identified in the facility drawings in accordance with MIL-STD-100, and installed hardness critical items shall be distinctively marked. Facility design and installation changes shall be assessed for potential HEMP hardness impacts prior to approval. The affected portions of the HEMP protection subsystem shall be retested when configuration changes occur after acceptance testing.

These requirements of MIL-STD-188-125 are for the purpose of establishing HEMP protection subsystem configuration baselines and baseline documentation during the facility acquisition. The resulting HCI and HCP identifications and technical data on functional and physical characteristics will then be used as the starting point for HEMP configuration management during the operations and support phase.

The HCI notations on drawings and markings on the physical components serve as a flag to alert personnel to the hardness criticality of the item. The design engineer or installation crew member who encounters one of these symbols should be directed to consult with the individual responsible for the HEMP protection before making any alterations to the configuration.

When a change is determined to be necessary or desirable, the standard establishes the requirement for a configuration control process to assess potential hardness impacts. Furthermore, if the modification is approved and implemented subsequent to acceptance, retesting (see section 16) must be conducted to verify that performance has not been degraded.

Approaches for satisfying these requirements are discussed in section 19.3. Additionally, this handbook addresses the development and execution of a plan for configuration

management during the operations and support phase, which is not covered by MIL-STD-188-125.

19.3 Applications.

19.3.1 Configuration management during facility design. Important activities of the HEMP configuration management program take place during facility design, building construction, and C-E equipment installation. The original configuration baselines for the HEMP protection subsystem are developed and documented in design analyses, drawings, and construction specifications. Usually, some baseline modifications are required during construction and equipment installation phases; these must be processed through change control procedures, and the documentation must be revised to reflect the as-installed configuration.

There are two options for formal planning of HEMP configuration management during the acquisition phases:

a. A HEMP configuration section may be included in an overall facility configuration management plan.

b. Identification of acquisition HEMP configuration management tasks, assignment of responsibilities for these tasks, methods, products, and scheduling can be addressed in the HEMP program plan (see section 21).

If an overall acquisition phase plan will be implemented for other engineering disciplines, HEMP configuration management should be integrated into it. Regardless of the choice, however, it is critical that the requirements and responsibilities be clearly delineated.

19.3.1.1 HEMP design analyses. HEMP analyses for a MIL-STD-188-125 hardened facility will generally be limited to PCI performance predictions for candidate electrical POE protective devices and response calculations to support the development of special protective designs. The design analysis reports must be reviewed for completeness and accuracy and preserved as configuration baseline documentation.

19.3.1.2 Design drawings. The facility drawings, along with the performance specifications (see 19.3.1.4), are the principal sources of baseline configuration data for the HEMP protection subsystem. It is critically important to the entire HEMP configuration management process, therefore, that these documents provide a complete and accurate description of the hardening.

Defining the topology of the electromagnetic barrier will usually be the first step in the HEMP design, and this step should be completed before the first (early preliminary) review. The location of the barrier should be indicated on floor plan and elevation drawings with very distinctive lines. The locations of personnel entryways and the penetration entry areas should also be shown. Figures 180 and 181 provide good examples of barrier markings, using an extremely heavy line to indicate the location of the facility HEMP shield.

Schedules of barrier penetrations and filter/ESA assemblies are required, and these will normally be included in the drawing package. The schedules will be discussed separately in 19.3.1.3.

Shield fabrication and POE protective device installation details must be provided in the drawings. These details must contain information in sufficient depth to ensure that configuration, dimensional, and other assembly requirements of MIL-STD-188-125 will be met. Furthermore, all hardness critical items and processes must be marked with the $\boxed{\text{HCI}}$ and $\boxed{\text{HCP}}$ symbols (no level designation required for HEMP) specified by MIL-STD-100 (reference 19-5) and the following note must be provided on the drawing:

> 'THIS DRAWING DEPICTS HARDNESS CRITICAL ITEMS (HCIs) AND (OR) HARDNESS CRITICAL PROCESSES (HCPs). ALL CHANGES TO OR PROPOSED SUBSTITUTIONS OF HCIs AND (OR) HCPs MUST BE EVALUATED FOR HARDNESS IMPACTS BY THE ENGINEERING ACTIVITY RESPONSIBLE FOR SURVIVABILITY."

These symbols and the note are to be placed on top-level drawings that show the hardness critical item or process and on the associated details, schematics, and wiring diagrams.

Special protective measures must also be shown in the drawings, at the comparable level of detail as that for the barrier elements. MIL-STD-100 requirements also apply to the marking of special protective HCIs and HCPs.

19.3.1.3 Schedules. The HEMP configuration documentation should include a complete schedule of all primary electromagnetic barrier and special protective barrier penetrations, usually as a sheet in the drawing package. The schedule serves as an aid in the POE minimization and control process and is used as a checklist in preparing HEMP test plans and the HM/HS plan. An example of a penetration schedule is presented and discussed in section 7.

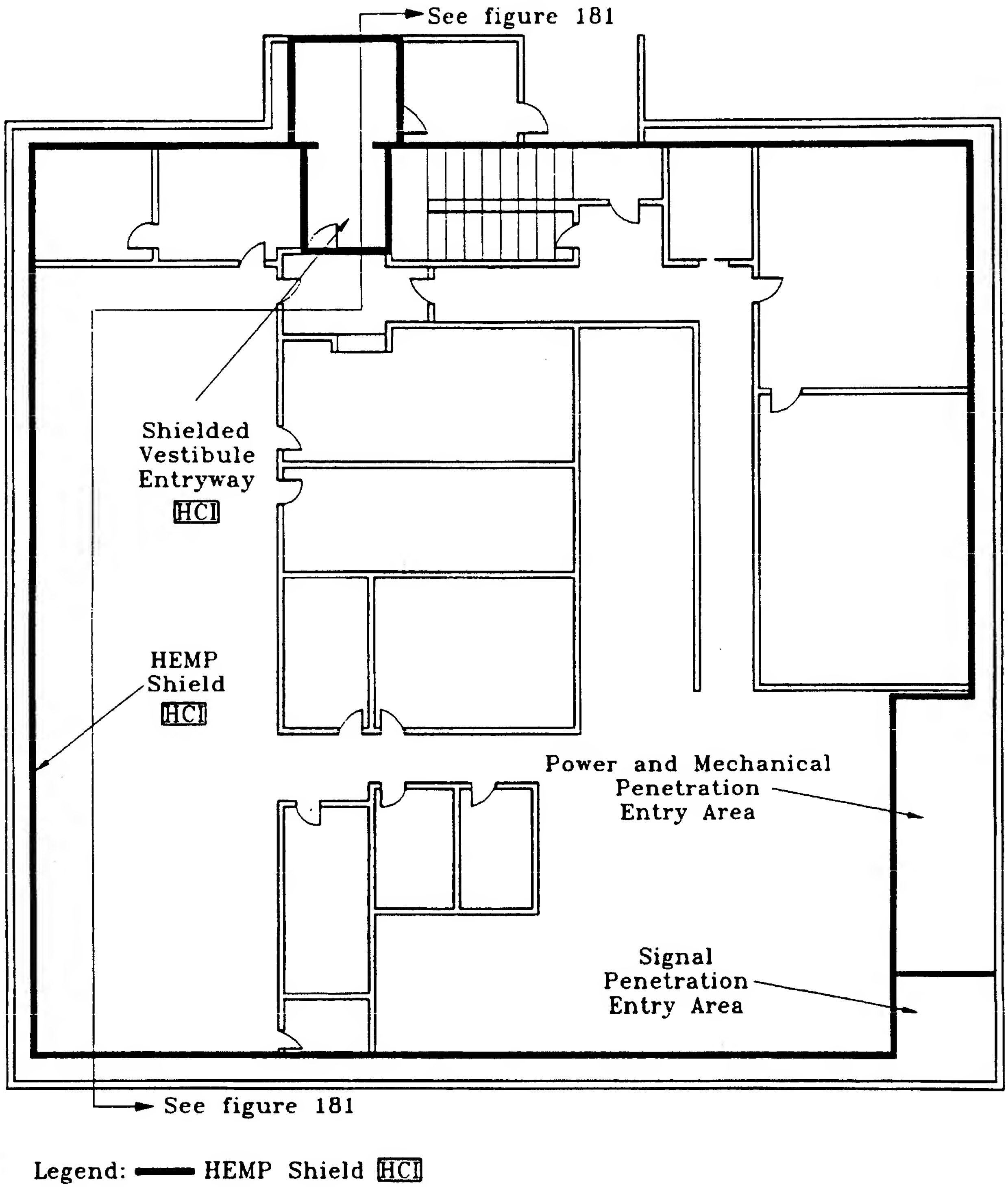
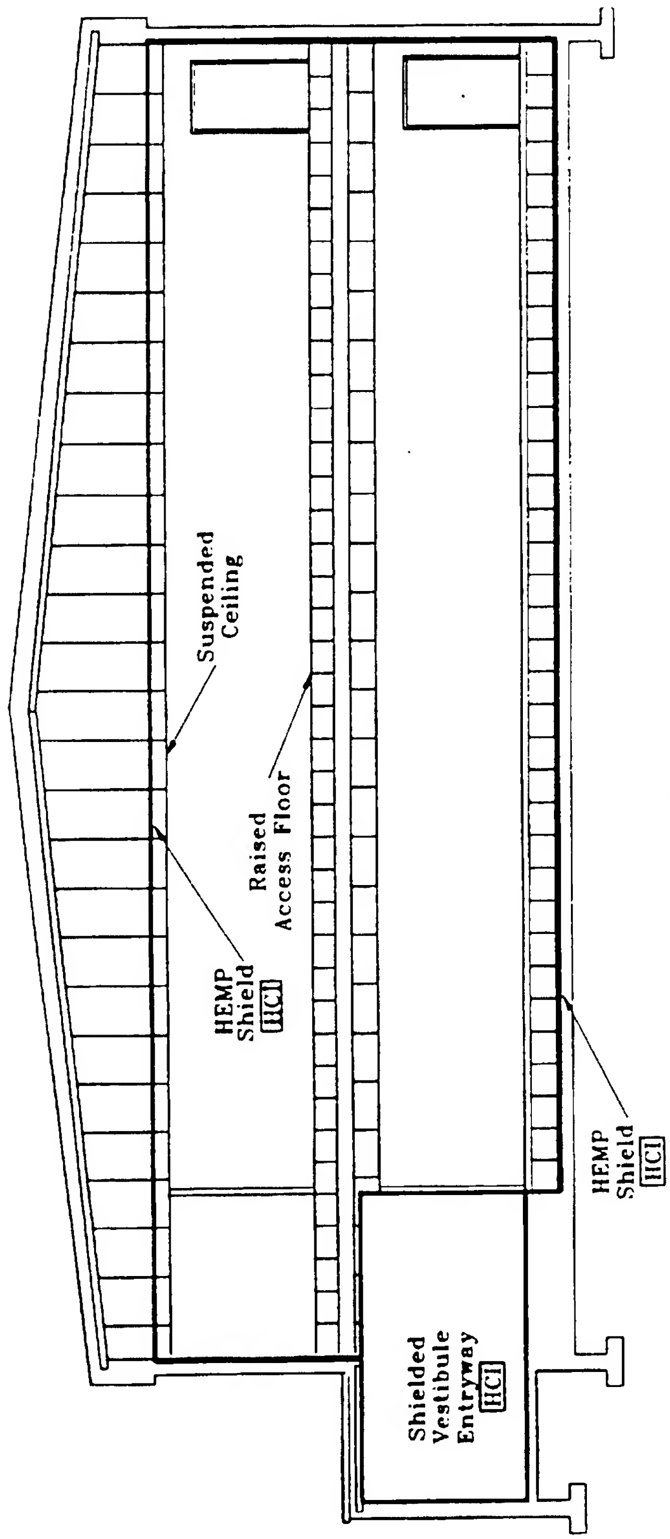


FIGURE 180. Floor plan indicating the location of the electromagnetic barrier.



Legend: —— HEMP Shield HCI

FIGURE 181. Section drawing indicating the location of the electromagnetic barrier.

Key information to be included in the penetration schedule includes the following items:

a. POE designation for tracking purposes – the example in section 7 uses an A designator for architectural POEs, M for mechanical POEs, etc.

b. A brief description of the purpose (personnel entryway, water pipe, commercial power line, etc.) of the POE and the type of POE protection

c. The POE location, including sheet numbers of the drawing showing the location

d. Sheet number of the drawing that illustrates the POE protective device installation detail

It is good practice to also provide a note that prohibits additional barrier penetrations unless approved by the Contracting Officer.

A separate filter/surge arrester schedule in the electrical drawings is also recommended in section 7. The same POE designations and descriptions used in the penetration schedule should be provided for ease of cross referencing. Key operating parameters of each protected circuit including voltage, current, frequency, and number of conductors should be tabulated. Principal performance requirements for the protective devices should also be shown in the schedule. For filters, these requirements include passband frequencies, maximum attenuation in the passband, and minimum rejection band attenuation specifications. Critical ESA parameters include dc breakdown voltage for spark gaps, varistor voltage at 1 mA dc current for MOVs, and extreme duty discharge current. All filter/ESAs should also be shown on the on-line electrical schematics.

It is desirable to have the schedule formats with at least sample entries at the early preliminary design review. The schedules should be nearly complete at the preliminary design review and fully complete for the final review.

19.3.1.4 HEMP protection subsystem specifications. The construction specifications for the HEMP protection subsystem serve several important hardness configuration management purposes, including the following functions:

a. They document the quantitative hardness performance requirements (or functional configuration baseline) for the facility HEMP shield, electromagnetic barrier POE protective devices, and SPMs.

b. They require the construction contractor to obtain Government approval of proposed changes to the hardening design.

c. They identify the baseline documentation and other relevant technical data to be provided.

It is the responsibility of the acquisition HEMP configuration manager to ensure that provisions supporting these functions are included.

MIL-STD-188-125 must be listed as an “Applicable Publication” whenever the HEMP protection subsystem must satisfy requirements of the standard. It is also necessary to explicitly refer to the standard in each individual provision where compliance is required. This statement applies to the “Submittals” and “Quality Assurance” sections, as well as the product performance requirement articles.

Although prohibitions on additional barrier penetrations and changes to HCIs and HCPs appear on the drawings, it is suggested that similar language be included in the specifications. The procedures for requesting Contracting Officer consideration of a proposed change will be part of the general specification provisions, rather than part of the HEMP section.

As a minimum, the construction contractor should be required to provide as-built drawings, manufacturers' data on all commercial HCIs, shop drawings on all fabricated hardening components, hardness assurance and acceptance test plans, and test data and reports. Copies of component specifications used by the construction contractor to acquire HCIs from commercial suppliers and data from factory and receiving performance tests should also be provided to the Government. The specifications should define requirements for these submittals in sufficient depth to ensure that useful documentation is obtained. Also, the Government's right to reject inadequate deliverables should be reserved.

Handbook appendix A presents a sample specification for a HEMP protection subsystem meeting MIL-STD-188-125 requirements. Examples of language addressing these configuration management issues can be found in this appendix.

19.3.2 Configuration management in the construction phase. The architect-engineer's drawings and specifications constitute the approved building configuration identification at the start of the construction phase. As a means of ensuring Government visibility into and control over the project, a formal change review and approval process is instituted at this time.

The level of configuration baseline detail also greatly increases during construction, as particular products are fabricated or purchased to meet the performance specifications.

Complete and accurate HEMP protection subsystem documentation is critical to effective hardness configuration management. All available HCI data must therefore be provided to the Contracting Officer. These data include HCI shop drawings, hardness critical component procurement specifications, vendors' drawings, and manufacturers' descriptive literature. Approved changes and additional information must also be incorporated at the appropriate level of detail into the facility as-built drawings.

19.3.2.1 Configuration change control. In nearly all military construction projects, one or more changes to the architectural-engineering drawings or specifications produced in the design phase will be initiated by the Government or contractor during building construction. These proposed changes should receive the same careful HEMP review as the original design.

If an overall facility Configuration Control Board is established to critique the proposed changes, the HEMP configuration manager should be a member. If no such board is created, this manager should be on the distribution list for proposed change packages. The proposal should be reviewed for potential impacts on the HEMP hardening, and recommendations should be provided to the approving authority.

A change occurs to the HEMP protection when a barrier POE is added or modified, when shield topology or fabrication methods are altered, when additional intersite conductors are provided, or when modifications of SPMs are required. If the change order includes any of these items, it should be thoroughly evaluated against MIL-STD-188-125 requirements and good HEMP protection practices. These changes should also be assessed with respect to reliability, maintainability, testability, and other support engineering disciplines, and impacts on the HEMP test program should be identified. Approval should be recommended only after determining that the mission hardness will not be adversely affected.

19.3.2.2 Identification of installed HCIs. MIL-STD-188-125 requires distinctive markings on installed HCIs to alert operators and maintenance personnel to the hardness criticality of the components. Such markings have been used in the past at a few facilities, and they have been successful in discouraging indiscriminate changes.

An HCI identification tag, which is being standardized for DoD use, is illustrated in figure 182. These markings may be plastic or metal plates securely affixed to the HCI, or they may be applied by painting. The frame and letters are black, and the background is flame orange. The "Reference Manual" is the hardness configuration management plan (see 19.3.4.1) and the "HCI Item #" is the designator for that item from the HCI list in the plan. The HCI nomenclature and federal stock number or manufacturer's part number

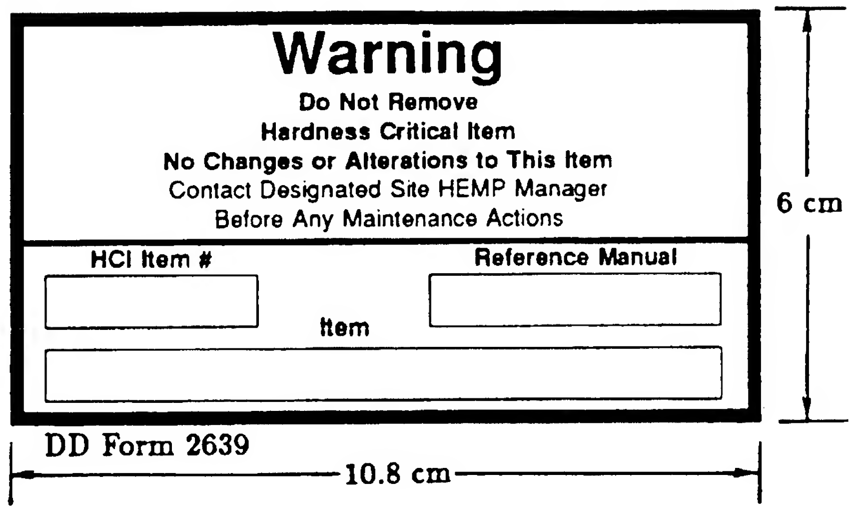


FIGURE 182. HCI identification marking.

are entered in the block entitled "Item." A cable tag containing the same information is used to identify a hardness critical conduit or shielded cable.

The dimensions indicated in figure 182 are those for large components; smaller versions can be employed where necessary. Suggested rules for placing these markings on various types of HCIs are as follows:

a. Shield surfaces – markings provided at approximately 1.2 m (4 ft) intervals in each direction on all accessible surfaces. Covering of the identification symbols by finish work such as interior wall panels or exterior siding should be allowed, but at least one marking should be visible when any single panel is removed.

b. Shield doors – one tag on each side of each door leaf at approximately eye level.

c. Equipment access covers - one tag on each side of the cover at approximately the geometric center [use 1.2 m (4 ft) spacing between markings for very large covers]

d. Piping POE waveguide sections and ventilation waveguide arrays - tags on each side of the electromagnetic barrier on the most easily visible surfaces. It is also suggested that flame orange stripes be painted at the ends of the waveguide sections.

e. Electrical POE protective device assemblies – tags on the interior and exterior access covers at approximately the geometric center. If practical, the transient suppression/ attenuation components should also be tagged.

f. HEMP protection conduits and cables - tags provided at approximately 1.2 m (4 ft) intervals along the exposed sections of the conduit or cable.

g. Shielded pullboxes and other rf enclosures – markings on all access covers or panels at approximately the geometric center.

h. Other special protective measures – tags installed at appropriate and visible locations.

19.3.2.3 As-built drawings and other configuration documentation. The minimum HEMP configuration baseline documentation to be provided by the construction contractor was previously listed in 19.3.1.4. It includes the following items:

a. As-built drawings

b. Catalog data on commercial HCIs and shop drawings for specially fabricated compo nents

c. Quality assurance and acceptance test plans, data, and reports

Requirements for the as-built drawings are the same as those for the architect-engineer's design drawings (see 19.3.1.2 and 19.3.1.3), but they are of course revised to reflect construction phase changes. The requirement for as-built drawings is critical and should not be waived.

Normal commercial standards apply to the manufacturers' data and shop drawing submittals. If additional information is needed, most manufacturers will supply it at an additional cost.

MIL-STD-188-125 provides quite explicit instructions for preparing the acceptance test plan and acceptance test report, and adherence to these requirements should be demanded. Unless otherwise prescribed in the specifications, the hardness quality assurance test plan and report and other specified documentation will be prepared in accordance with commercial practices.

19.3.3 Configuration management during equipment installation. From the perspective of HEMP configuration management, the C-E equipment installation phase is a continuation of the construction project on a limited scale. The activities and procedures

for change control, identification of installed HCIs, and documentation upgrades should therefore be continued during this time period.

19.3.4 Operations and support phase configuration management. A formal HEMP configuration management plan for the facility operations and support phase is considered essential. The document should be developed during the acquisition cycle and provided to the operators and maintenance staff when they assume responsibility for the site.

The HEMP configuration management plan may be a part of an overall facility configuration management plan, a chapter or volume of an overall HM/HS plan, or a separate document. Integration of HEMP configuration management into the overall plan for the facility is preferred, when an overall plan is required. Preparation of the plan is not a usual element in either a facility design contract or a construction contract; responsibility for this task must therefore be determined by the HEMP acquisition program manager and assigned in the HEMP program plan (see section 21).

19.3.4.1 HEMP configuration management plan. The operations and support phase HEMP configuration management plan is intended to provide detailed and site specific instructions for implementation of the hardness configuration management program. Therefore, the plan must define all of the following elements: HEMP configuration management policies and requirements, organizational responsibilities for execution of the plan, subsystem and HCI essential characteristics data, and detailed procedures. Part of this information, particularly policy statements and some of the technical data, can be incorporated by reference, rather than being completely included in the text.

An outline of the plan, developed from the guidance in MIL-STD-973 and tailored to a MIL-STD-188-125 HEMP hardened facility design, is presented in table XX. The suggested configuration management organization is headed by the site commander, assisted by a HEMP configuration manager with supervisory responsibility for the HEMP program. Other designated positions may include the membership of an overall facility Configuration Control Board, a technical data manager, and assistants for other functions.

The formal change control procedure for review and approval of proposed facility modifications is probably the most important part of the plan. All configuration changes, including major retrofits and minor modifications and those planned to be done by outside agencies, as well as those to be implemented locally, must undergo this review. The procedure addresses the following areas:

a. The nature and depth of information on proposed changes to be submitted for review

TABLE XX. Hardness configuration management plan outline.

HARDNESS CONFIGURATION MANAGEMENT PLAN OUTLINE

I. INTRODUCTION - Identify the subject facility: state the purpose of the plan and provide an overview of the contents.

II. ORGANIZATION - Describe organizational structure and responsibilities for hardness configuration management: identify policy directives, standards, regulations. and other references applicable to the program: describe relationships to the organization for overall facility configuration management.

III. HEMP PROTECTION SUBSYSTEM DESCRIPTION – Provide functional and physical descriptions of the HEMP protection subsystem, including the following items:

A. Site plan

B. Floor plan and elevation drawings, showing the location of the electromagnetic barrier and the protected volume

C. Shield description including materials, thicknesses, joining methods, and selected assembly details

D. List of barrier POEs and POE protective devices; provide selected details of protective device installations; provide manufacturers' data sheets for commercial HCIs in an appendix

E. Provide descriptions and HCI lists for all special protective measures

IV. BASELINE DOCUMENTATION - Identify all formal documentation for the HEMP protection subsystem, typically including some or all of the following items:

A. HEMP protection subsystem specifications

B. Facility drawings and HCI lists

C. HEMP analysis and design reports

D. HCI specifications, commercial literature, and related materials

E. HEMP test plans, test data, and test reports

F. HM/HS plan

G. Other technical data

TABLE XX. Hardness configuration management plan outline (continued).

V. PROCEDURES – Provide detailed configuration management procedures, including procedures for the following activities: A. Review and approval of proposed HEMP hardness configuration changes including facility modifications and HCI substitutions B. Reassessment of HEMP hardening requirements when mission or threat changes occur C. HEMP documentation maintenance including storage and revisions D. HEMP hardness configuration auditing
VI. HARDNESS CONFIGURATION REPORTING - Describe requirements and procedures for HEMP configuration and status reporting, if applicable.

b. Identification of personnel to perform the review and specific designation of those responsible for assessing HEMP hardness impacts

c. Guidelines for determining when and how a change affects the HEMP protection

d. Methods for obtaining outside HEMP expertise, when necessary

e. Format requirements for reporting findings and recommendations from the review

Appropriate controls for ensuring a satisfactory HEMP design and updating the HEMP baseline documentation must be instituted when a change is determined to have hardness impacts, but these are beyond the scope of the review procedure.

There may be some variations of the control procedure, depending upon the complexity of the proposed change. If the modification is an HCI substitution because the original component is no longer available, for example, the HEMP configuration manager might be the sole reviewer.

The facility modifications of concern are principally changes in the physical characteristics. However, the functional HEMP baseline can also be affected by changes in

the mission of the site and changes in the threat scenario or environment definition. One extreme would be the elimination of HEMP survivability requirements, allowing hardness configuration management and HM/HS to be discontinued. At the other end of the scale, enhanced threat fields might be possible with state of the art improvements in nuclear weapon technology. The plan should include a procedure for reassessment of the hardening requirements if such changes do take place.

All inaccuracies and deficiencies in the baseline documentation for the HEMP protection subsystem must be corrected, and updates of the data will be required when site modifications are implemented. The third procedure identified in the configuration management plan outline provides specific instructions for accomplishing documentation revisions. Standard forms for originating changes are to be included, and the on-site processing steps are to be defined in detail.

The last of the procedures listed identifies requirements and methods for hardness configuration audits. The audit is accomplished by a physical survey of the HEMP protection subsystem to ensure that the documentation correctly reflects the as-installed configuration and that the various data items are consistent with each other. It is recommended that periodic audits be performed as part of the pretest site inspection before each hardness surveillance/reverification measurement program.

Data item descriptions DI-E-3108 and DI-CMAN-80858A should also be reviewed when preparing the HEMP configuration management plan.

19.3.4.2 Implementation. The principal HEMP configuration management tasks during the operations and support phase of the facility life cycle are to maintain the hardness baselines and baseline documentation in accordance with the plan. Except for HEMP assessments of complex site modifications or threat changes, these tasks can be accomplished within the capabilities and skill levels resident in the normally assigned facility staff. In the exceptional cases, assistance should be requested from the military department centers for HEMP expertise or from the Defense Nuclear Agency. The key to successful implementation is informed decision-making on hardness-related matters.

19.4 References.

19-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

19-2. "Defense Acquisition," DoD Directive 5000.1 (effective), Dept. of Defense, Washington, DC.

19-3. "Defense Acquisition Management Policies and Procedures," DoD Instruction 5000.2 (effective), Dept. of Defense, Washington, DC.

19-4. "Military Standard - Configuration Management," MIL-STD-9'73 (effective), Dept. of Defense, Washington, DC.

19-5. "Military Standard - Engineering Drawing Practices," MIL-STD-100 (effective), Dept. of Defense, Washington, DC.

20. HARDNESS MAINTENANCE/HARDNESS SURVEILLANCE

20.1 Basic principles. HEMP-hardened, ground-based C^4I facilities are designed, constructed, accepted, and verified in accordance with MIL-STD-188-125 (reference 20-1) and the guidance provided in this handbook. Once the HEMP protection subsystem in a facility has been accepted and verified, HM and HS are employed to ensure that the mission-essential equipment remains protected.

A typical facility will include numerous systems, including the HEMP protection subsystem, and each of these must be maintained in a state of readiness that is compatible with the mission requirements. Each of these maintenance programs includes an appropriate combination of preventive maintenance, corrective maintenance, inspections, and tests for the particular hardware to be maintained. The HM/HS program consists of these elements, as needed, to preserve the HEMP hardness and survivability of the mission-critical systems.

One aspect of HM/HS is unique, however. Most of the systems perform the same functions during peacetime and times of conflict, and failures are routinely detected and corrected during normal operations. Since the HEMP protection subsystem functions only when an attack occurs, faults may not be discovered during routine operations. To compensate for this difference, a higher level of surveillance is required to maintain readiness.

The process for developing and implementing the HM/HS program follows traditional integrated logistics support principles. It begins in the earliest stage of facility definition with the establishment of reliability, availability, and maintainability requirements and formulation of the hardness maintenance and surveillance concepts.

During the building design and construction and the equipment planning and installation phases, logistics support analysis is performed. The outputs of the integrated logistics support program form the basis of the HM/HS plan for the operational phase of the hardened facility life cycle. These outputs include the maintenance procedures, lists of required spare parts/replacement parts/supplies/special tools/special test equipment, HEMP protection subsystem technical data, related training materials, and configuration management requirements. The documentation of these items provide the necessary information and instructions for implementing the HM/HS program.

During the operation and support phase, the HM/HS program is implemented in accordance with the procedures provided. The installed hardening features are maintained and their performance is monitored. Facility modifications must also be controlled so that

the mission HEMP survivability requirements continue to be met. Revisions to the HM/HS program are made if the plan is found to be inadequate and when facility modifications affecting the HEMP protection subsystem occur.

This section presents the requirements and elements of the HM/HS program for the HEMP protection subsystem of a fixed, ground-based facility. As a background for this information, subsections 20.1.1 through 20.1.4 present a general discussion of hardness critical items and processes, hardness maintenance, and hardness surveillance.

20.1.1 Hardness critical items and assemblies. A HEMP hardness critical item is any item, usually at the individual component level, having performance requirements for the specific purpose of providing HEMP protection. A top-level assembly containing HEMP HCIs is a HEMP hardness critical assembly.

While some hardness critical items and assemblies may have no function other than HEMP protection, this is not exclusively the case. The HEMP shield can also provide isolation for other electromagnetic effects such as TEMPEST and lightning protection. Furthermore, an HCI may have HEMP performance requirements and other performance specifications that are totally unrelated to HEMP and other electromagnetic protection functions. An example of the latter type is an interface circuit element with a critical transient withstanding specification and an unrelated communication signal processing function.

The HEMP shield and all POE protective devices are obviously hardness critical. All devices installed as special protective measures are also HCIs. Collectively, the HCIs constitute the HEMP protective subsystem. The purpose of the HM/HS program is to maintain the HEMP performance of HCIs and HCAs at an acceptable level.

The assembly level at which to identify, track, and maintain the HEMP protection subsystem should be guided by the definition and appropriate discretion. A filter/ESA POE protective device should be identified as a hardness critical assembly and maintained at the assembly level. The individual filters and surge arresters are also designated as HCIs, since they have specific HEMP performance specifications. Enclosure covers and rf gaskets are HCIs only when the compartments have HEMP shielding requirements. Common items such as terminal posts, bolts and nuts, or mounting hardware, while it is important to inspect and maintain these items periodically, should not be tracked as HCIs unless they are specially fabricated for HEMP applications.

Factors to be considered when initially identifying and selecting hardness critical elements should include, but not be limited to, the following:

a. All hardness critical items and assemblies must be identified.

b. Federally stock-numbered items should be used, where possible.

c. The same part, by manufacturer and model number, should be used in all applications with the same requirements. Parts from the same product line should be used in applications with similar requirements.

In accordance with MIL-STD-100 (reference 20-2), all project drawings and parts lists must identify individual HCIs. The drawings also identify the locations of the HCIs. Drawings that depict HCIs or HCPs should have the following note:

> "THIS DRAWING DEPICTS HARDNESS CRITICAL ITEMS (HCIs) AND (OR) HARDNESS CRITICAL PROCESSES (HCPs). ALL CHANGES TO OR PROPOSED SUBSTITUTIONS OF HCIs AND (OR) HCPs MUST BE EVALUATED FOR HARDNESS IMPACTS BY THE ENGINEERING ACTIVITY RESPONSIBLE FOR SURVIVABILITY."

HCIs must also be listed in the HM/HS program documentation. Figure 183 contains sample entries for such a listing. The hardness critical element identification number should correlate with the POE identification number that is used in the penetration schedule, when applicable.

20.1.2 Hardness critical processes. Hardness critical processes are necessary fabrication and installation methods developed to ensure proper performance by an HCI. These HCPs must be incorporated into HCI repair and replacement procedures and HCI reprocurement specifications, where appropriate.

20.1.3 Hardness maintenance. Hardness maintenance consists of preventive and corrective maintenance actions intended to maintain required performance levels of hardness critical items and assemblies. These actions are performed by the resident maintenance organization, when possible, and by a depot activity or contractor if they require capabilities or equipment not available at the site.

Preventive maintenance includes all scheduled maintenance actions. They are performed on a regular basis, even though the condition and performance of the HCI maybe at a satisfactory level. Preventive maintenance includes scheduled adjustments, cleaning, and replacements of items with limited lifetimes. Servicing requirements such as lubrication are included in this category.

Hardness Critical Assembly/Item	Assembly/Item Description	Location
E 10	Filter/ESA assembly; manufacturer _________; model number _________; serial number _________	Penetration entry area
E 10 A	Filter (4 ea); manufacturer _________; model number _________	E 10
E 10 B	ESA (4 ea); manufacturer _________; model number _________	E 10
E 10 C	rf gasket, manufacturer _________; drawing or part number _________	E 10
M 15	1 m x 1 m battery room exhaust honeycomb WBC; drawing number _________	Room 102, west wall
M 15 A	Honeycomb material; manufacturer _________' model number _________	M 15

FIGURE 183. Typical HCI list.

All hardness preventive maintenance on the HEMP protection subsystem recommended in this handbook is expected to be within the capabilities and skill levels of the local facility personnel. The preventive maintenance tasks are, therefore, combined with organizational hardness surveillance inspection and testing tasks (see 20.3.7) into preventive maintenance and inspection (PMI) procedures. These procedures are discussed in subsection 20.3.5.

Hardness corrective maintenance includes all unscheduled maintenance actions. Such actions are undertaken, when excessive degradation or failure of an HCI is detected, to restore the HEMP protection subsystem to a satisfactory condition and level of performance. Corrective maintenance includes removal, repair or replacement, reassembly, and checkout of the completed work.

Hardness corrective maintenance procedures are discussed in 20.3.6. Some of these repairs are within the capabilities of local facility personnel, while others are not. In the latter case, the corrective maintenance must be performed by an intermediate or depot maintenance organization or by a contractor.

20.1.4 Hardness surveillance. Inspections and testing of the HEMP protection subsystem and its HCIs are included in hardness surveillance. These HS actions only observe and monitor the condition and performance of the hardening elements. If excessive degradation or failure are found by hardness surveillance, the defective hardness critical element is repaired or replaced in accordance with a corrective maintenance procedure.

Surveillance inspections and tests that are performed by local facility personnel are termed organizational HS. Essentially all of the HCI inspections and many of the measurements recommended in this handbook fall into this category. The inspections are predominantly visual; the observable indications of degradation or failure can be recognized by conventional mechanical and electrical technicians with specialized HEMP training. Organizational HS tests employ the built-in shield performance monitor and portable SELDS instruments. This test equipment is expected to be available at each HEMP-hardened facility, and local maintenance personnel are expected to be trained to use it.

As previously mentioned, the organizational HS tasks have been integrated with hardness preventive maintenance tasks into PMI procedures.

This handbook also recommends that a more extensive surveillance/reverification test be performed on HEMP-hardened facilities at five- to seven-year intervals. The requirements for this test program involve the use of high-level HEMP simulation sources

and specialized data acquisition and processing equipment. operation of this test equipment and analysis of the hardness surveillance/reverification test results require personnel skills and experience that are not expected to be available locally. Therefore, the hardness surveillance/reverification testing must be performed by an intermediate or depot maintenance organization, another designated Government testing activity, or a contractor.

20.2 MIL-STD-188-125 requirements.

> 4.1.1 HEMP protection overview. . . . Because normal operational experience may not indicate the condition of the HEMP protection subsystem, thorough verification testing, hardness maintenance, and hardness surveillance after deployment are necessary. . . .

> 4.2 Hardness program management. . . . Design and engineering, fabrication, installation, and testing activities shall be managed to accomplish the following objectives:
>
> a. To provide a HEMP-protected facility design based upon verifiable performance specifications
>
> b. To verify hardness levels through a cost -effective program of testing and analysis
>
> c. During the acquisition process, to develop a maintenance and surveillance program which supports the operational phase of life-cycle HEMP hardness

> 5.1.9 Reliability and maintainability. The HEMP protection subsystem shall be designed and constructed to be rugged, reliable, and maintainable. . . .

> 5.1.11 Testability. The HEMP protection subsystem shall be designed and constructed to accommodate quality assurance, acceptance, and verification testing and hardness maintenance and hardness surveillance. . . .

> 5.1.19 Configuration management. Hardness critical items and hardness-critical processes shall be identified in the facility drawings in accordance with MIL-STD-100, and installed hardness critical items shall be distinctively marked. . . .

MIL-STD-188-125 is an acquisition standard for HEMP-hardened facilities; it directly addresses the elements of HM and HS that must take place before the site is operational. The need for effective hardness maintenance and surveillance is recognized. Furthermore,

MIL-STD-188-125 specifies development of the HM/HS program during the acquisition phase and requires that reliability, maintainability, and testability be incorporated into the HEMP protection subsystem design and construction. Implementation of the required maintenance procedures should begin immediately after the hardness critical items and assemblies are accepted by the Government.

20.3 Applications.

20.3.1 General guidance. The goal or objective of an HM/HS program is to ensure that the HEMP protection system is maintained in a satisfactory state of hardness for the planned lifetime of the facility. While many approaches for achieving this goal are possible, the program must be unobtrusive to the site, it must be complementary to the way things are to be done at the site, and it must be cost effective. If a HEMP protection system is to perform properly at all times, it must be principally maintained using local resources and local personnel.

There is a fine line between the number of things that can be done to maintain a facility and the number of things that must be done to maintain a facility. A prudent goal for the HM/HS program is to construct a program that consists of an adequate number of HM procedures, coupled with a sufficient number of HS tests, to provide an acceptable level of confidence in the adequacy of the HEMP protection subsystem. In attempting to meet this goal, the handbook has relied heavily upon previously published information in reference 20-3.

Satisfactory implementation of the recommended HM/HS program will provide an acceptable degree of confidence that:

a. The HEMP barrier is continuous and free of visible defects.

b. All barrier POEs are protected, and the protective devices have the appearance of being in good working order.

c. Corrosion protection measures for the HEMP protection subsystem are being satisfactorily maintained.

d. Shielded doors, door controls, and door interlocks are operable, and the electromagnetic door seals are intact.

e. Shielded equipment access covers are installed and all fasteners are in place.

f. WBC protective devices are installed, are free of visible damage, and have not been compromised.

g. Electrical filters are installed on all penetrating conductors; their appearance and operating temperatures are normal.

h. ESAs are installed on all penetrating conductors and have no visible indication of damage or failure.

i. Shielded conduits appear to be intact, and covers on all shielded enclosures are in place.

j. All required special protective devices are installed and appear to be in good working order.

k. A periodic program of HEMP protection performance measurements exists for finding deficiencies that cannot be visually detected.

Maintenance and surveillance tasks for the HEMP protection are to be integrated with the maintenance activities for other subsystems at the facility. The same scheduling and tracking methods should be employed and the same types of maintenance records should be kept. An HM/HS program that is entirely separate from the normal procedures is more likely to be ignored.

If the initially defined HM/HS program does not satisfactorily maintain the hardness and if the instructions do not provide the level of detail required by the maintenance personnel, the program, procedures, and maintenance intervals should be revised as necessary. Similarly, maintenance intervals can be relaxed when on-site experience indicates that they are too short. It is strongly recommended that the HM/HS program be critically reviewed on a regular basis during the operational phase and that experience-based improvements be incorporated.

Another important point of general guidance is the need for HEMP trained and experienced personnel for developing the HM/HS program and for surveillance. The HM/HS plan development effort requires both knowledge of HEMP principles and practices and intimate familiarity with the particular facility. Similarly, while anyone can look at a HEMP shield or filter/ESA assembly, only a trained inspector knows how to effectively focus the examination and recognize problems. Training for site personnel is addressed in 20.3.8.

20.3.2 HM/HS concept development. The initial activity in planning for hardness maintenance and surveillance is development of the HM/HS concept. This step takes place in parallel with definition of the HEMP hardening approach and the hardness verification testing approach during the planning, programming, and budgeting phase.

The HM/HS concept definition includes designation of the organizations to be responsible for the various levels of hardness maintenance, inspection, and testing in accordance with service policies. Essentially all of the hardness preventive maintenance and inspections recommended in this handbook should be within the capabilities of maintenance personnel assigned to the facility or base. Some hardness testing and repairs require HEMP expertise and equipment that is usually not available at the facility or base; in these instances, support from an intermediate maintenance group, depot, other logistics agency, or contractor will be required. The organization responsible for preparing the HEMP protection subsystem technical manual must also be identified.

This designation of responsible organizations is a critical element in the related staffing, budgeting, and scheduling decisions. It also provides a necessary input to guide the development of the HM/HS plan, detailed procedures, and training materials and to ensure that appropriate funds are budgeted.

Requirements for HEMP protection subsystem built-in test equipment should also be determined as part of the HM/HS concept development. MIL-STD-188-125 specifies that a built-in capability to monitor the performance of the HEMP shield must be provided, and shield monitoring designs are discussed in section 17. Built-in testers for HEMP filters and surge arresters are under study, and practical and effective designs may become available in the future. The facility design requirements document should explicitly identify built-in test equipment to be supplied as part of the HEMP protection subsystem.

20.3.3 Reliability, maintainability, and testability in design and construction. Prerequisites for successful hardness maintenance and hardness surveillance are that the HEMP protection subsystem be designed and constructed to be reliable, maintainable, and testable. The hardening must also be engineered for human factors and safety so that the hardware, task requirements, and work environments are compatible with the capabilities and limitations of the personnel who must operate and maintain the system. A major fraction of the HM/HS planning effort is reviewing the design and inspecting the implementation to ensure that the as-built HEMP protection has these attributes. Reliability, maintainability, testability, and human engineering considerations and guidelines are addressed in handbook sections 17 and 18.

20.3.4 HEMP protection subsystem technical manual. In accordance with DoD policy for military systems with nuclear survivability requirements, a maintenance and surveillance program that supports the operational phase of life-cycle hardness must be developed during the acquisition process. A detailed outline for the HM/HS program documentation for a facility that is HEMP hardened as specified in MIL-STD-188-125 is

presented in section 21. It is strongly recommended that the document be provided as a HEMP protection subsystem technical manual.

As a minimum, the HM/HS plan or HEMP protection subsystem technical manual should include the following items:

a. A detailed description of the HEMP protection subsystem in sufficient depth to serve as the configuration baseline; it should also include complete identification of HCIs and lists of recommended spare parts, repair parts, supplies, special tools, and special test equipment

b. Detailed procedures for all required preventive maintenance, inspections, and tests

c. Detailed corrective maintenance (troubleshooting and repair) procedures

d. Detailed configuration management requirements

e. Training requirements and materials

This section discusses the maintenance procedures and training requirements. The configuration management aspects of HM/HS are addressed in section 19.

The HEMP protection subsystem technical manual is developed by the organization designated in the HM/HS concept to accomplish this task. Inputs are obtained from a variety of sources. The architect-engineer's design drawings initially identify the required HCIs and HCPs, and the construction specifications prescribe the hardness critical performance parameters and installation methods. Construction contractor submittals including shop drawings, manufacturers' data for the specific components installed, the contractor's and manufacturers' recommended operating and maintenance procedures, and as-built drawings provide information at a significantly greater level of detail. Hardness assurance, acceptance, and verification test reports contain the baseline performance data.

The overall framework for the document should be based upon the generic HM/HS plan for HEMP-hardened, ground-based facilities for the service that will maintain the facility, if such a generic plan is promulgated.

Preparation of the HEMP protection subsystem technical manual occurs during the design and specification development, construction and acceptance testing, and C-E equipment installation phases. The verification test plan and report are supplied when they become available. At least a preliminary version of the HM/HS plan must be provided when the Government accepts the building from the construction contractor, so that maintenance and surveillance can be implemented on HCIs provided in the construction phase.

The complete HM/HS plan must be available by the end of the equipment installation and checkout effort.

The organization responsible for developing the HM/HS program should be a participant in the design review and construction surveillance processes, where practical. This provides an opportunity to recommend data requirements to support preparation of the plan for inclusion in the construction specifications and the equipment installation work statement. It also provides the access for acquiring the HEMP protection subsystem and component information needed to perform the task.

20.3.5 Preventive maintenance and inspection procedures. Preventive maintenance activities are performed periodically to ensure that the HEMP protection system and its associated HCIs are functioning satisfactorily. Generally, PMIs consist of inspections, adjustments, cleaning, and some limited testing. While inspections and adjustments alone cannot provide a quantitative measure of the hardness level, they can provide an early indication of potential hardness degradations due to damage, aging, improper maintenance, or inadvertent compromise of the hardness protective features. Identification of a developing problem through performing PMIs leads to corrective action before a more serious and compromising fault occurs.

Experience from actual hardness maintenance programs indicates that the most common cause of hardness degradation is inadvertent compromise through improper use, repair, maintenance, or replacement of a hardness protective feature. A simple example is the case of missing or damaged fingerstock in an rf shielded door. If there is an in-place HM/HS program, this condition should not exist. Accountability would make it highly unlikely that the problem would go undetected for an extended period. Equally important, repairs would be made in an expeditious manner. Thus, hardness maintenance inspections are a very important function in a HM/HS program.

PMI procedures consist of those activities that can be performed on a hardness critical item or assembly to visually inspect its condition, to look for degradation and damage, and to verify that all constituent components, parts and materials are in place and in satisfactory condition. If simple adjustments are to be made, such as tightening cover screws, this operation is part of the procedure. The normal guideline for the content of a PMI procedure is that it should cover all operations that apply to that hardness critical element and can be performed by the specified maintenance technician using the specified tools and supplies. Preventive maintenance and inspection is the principal maintenance activity for ensuring that there is no unacceptable degradation of the HEMP protection subsystem. PMIs accomplish this by eliminating or reducing problems through regularly

scheduled actions. In addition, PMIs identify deficiencies before they become failures that compromise the HEMP protection of the facility.

Other than inspection, most of the HCIs require little in the way of regular maintenance to ensure that they have not been damaged, modified, or removed. These inspections must be conducted at prescribed intervals in order to maintain satisfactory confidence in the adequacy of the HEMP protection. Additionally, the PMI procedures must be conducted whenever there are changes, modifications, or any type of construction which could affect the HCIs. Table XXI shows the typical degradation mechanisms of HCIs and also indicates appropriate preventive maintenance and inspection techniques which should be used to identify the problems.

Preventive maintenance and inspection procedures should be developed for every HCI or HCA. Generic information provides no useful guidance to the maintenance technician. Specific instructions for the specific HCIs at the particular facility are required. This same philosophy is also true for the normal non-HEMP facility maintenance actions. As an example, the generator PMI procedures are written to provide specific guidance for maintaining the actual generators installed at the location. Since generators differ, if the generator mechanic had only generic generator preventive maintenance instructions, the desired maintenance could not be performed.

For each PMI procedure, certain information must be provided—what must be done, by whom, when, how, how long it should take, what support is needed, what are the success criteria, what to do if there is a failure, and what are the coordination requirements. Figure 184 is an example of a PMI procedure. The specific procedure depicted is not the important point. Instead, the content and type of presentation should be evaluated. The form, format, and type of presentation are similar to the information normally contained in non-HEMP maintenance and inspection procedures. The following information should be provided in each PMI procedure:

a. Objective – describes the overall goal of the PMI procedure.

b. Scope - lists the specific items addressed by the PMI.

c. Notes - provides specific comments which are relevant to the PMI.

d. References – indicates figures or drawings applicable to the PMI.

e. Personnel requirements – identifies the number and type of maintenance personnel required to accomplish the task.

TABLE XXI. HCI degradation mechanisms.

Protective Feature	Degradation Mechanism	PMI Technique	Frequency
HEMP shield	Defective welds Corrosion	Inspection Performance check	Monthly Annually
Shielded doors	Broken fingerstock Warped frame Warped doors Dirt Wear Defective welds Corrosion	Inspection and cleaning Performance check Major cleaning and lubrication	Monthly Quarterly Annually
Shielded access covers	Defective welds Corrosion Gasket damage or wear Missing bolts	Inspection Performance check (gasketed covers) Performance check (welded covers)	Monthly Quarterly Annually
Piping WBCs	Defective welds Corrosion	Inspection	Annually
Ventilation and fiber optic WBCs	Defective welds Corrosion Penetrating conductors	Inspection Performance check (honeycomb WBCs) Performance check (welded WBC panels)	Monthly Quarterly Annually
Filter/ESAs	Overstress Improper installation Bypassing/removing Aging Defective welds Corrosion	External inspection Shielding performance check Internal inspection	Monthly Annually Biannually
Conduits	Defective welds Corrosion Water intrusion	Inspection	Annually
Shielded enclosures	Improper construction or installation Defective welds Corrosion Gasket damage or wear Missing bolts	External inspection Internal inspection (gasketed covers)	Monthly Annually
SPMs	Installation-specific problems	As required	As required

PMI-4 Inspect Waveguides-Below-Cutoff (WBC)

OBJECTIVE:

This preventive maintenance and inspection (PMI) procedure preserves the shielding effectiveness of waveguides-below-cutoff (WBCs).

SCOPE:

This PMI covers piping WBCs, ventilation WBCs, and fiber optic WBCs.

NOTES:

1. Because of their placement, some WBCs are not easily accessible for inspection from both sides. Although inspection from both sides is desired, if one side is not accessible, inspection from the accessible side only will be adequate.

2. WBCs are often sealed with a putty or foam to control air flow between the interior and exterior and to prevent corrosion inside the WBC. Inspection of the interior or the WBC is generally not possible with the seals in place.

REFERENCES: TM-__________. figure _____

PERSONNEL REQUIREMENTS: 1 mechanical maintenance technician, skill level 5

TIME REQUIRED (hours):

PREPARATION 1.0

ACTIVITIES 2.0

SAFETY:

No special hazards are involved. Normal site safety requirements are to be observed. Caution should be exercised when using ladders.

SECURITY:

Normal site security requirements, access requirements, and procedures are to be observed.

FIGURE 184. Sample PMI procedure.

TOOLS:

Flashlight	2-m step ladder
Stiff bristle brush	Wire brush
Putty knife	

SUPPLIES:

Clean cloths	Sealing putty or foam

FREQUENCY: Monthly

INSTRUCTIONS:

Perform the following PMI activities at the interval indicated, Perform the indicated maintenance to correct any discrepancies.

1. To the extent possible, visually inspect the WBC. Unless the WBC has a required seal, it should be free of any obstructions, penetrations, moisture, rust, or corrosion. IN NO CASE SHOULD AN ELECTRICAL CONDUCTOR BE PERMITTED TO PENETRATE A WBC.
2. If the WBC has a required seal, inspect the sealing material. It should form a solid contact along the inside shell of the WBC. If the seal has gaps or appears damaged, remove sealing material with putty knife and visually inspect the WBC for obstructions, penetrations, moisture, rust, or corrosion.
3. Remove any obstructions or penetrations found in the open WBC. DO NOT REMOVE UNDAMAGED SEALING MATERIAL. Clean the WBC with a clean cloth. If rust or corrosion is found, clean with wire brushes followed by a clean cloth. Repaint as necessary.
4. Check the WBC for cracks or voids on the WBC itself, as well as on its circumferential weld to the facility shield.
5. Any damage or cracks should be repaired in accordance with CM-8.
6. If the WBC had been sealed and the seal was removed because of damage, reseal WBC with similar sealing material (putty or foam). Ensure that seal makes a solid contact around inside shell of WBC.

FIGURE 184. Sample PMI procedure (continued).

f. Time required - gives an estimate of the number of hours required to accomplish the PMI. The preparation/travel is the time estimate for gathering materials and tools and traveling to the location where the PMI is to be performed. The activity time is the estimate of the time to accomplish the PMI.

g. Safety – stipulates special safety requirements. Appropriate site safety procedures are to be observed.

h. Security - provides special security procedures which must be observed so that the PMI can be conducted.

i. Tools – lists special tools required for the PMI. Normal electronics or mechanical technician tools are not explicitly identified.

j. Supplies – lists supplies which are required for the PMI.

k. Frequency - specifies the frequency of performing the PMI.

l. Instructions - gives the specific step-by-step procedure that is to be performed and identifies satisfactory and unsatisfactory conditions. The PMI activities may include some minor repairs to correct deficiencies. If the required repair is too extensive or requires special tools, supplies, materials, or expertise, the appropriate corrective maintenance procedure is referenced.

The needed PMI methods are a strong function of the type of HCI and the maintenance philosophy. The following paragraphs cover representative HCIs and the various types of maintenance and inspections that should be performed.

20.3.5.1 HEMP shield. Regular visual inspections of the HEMP shield should be made on a monthly basis. No special tools are required other than adequate lighting, a pick, a wire brush, and a magnifying glass. The performance of the shield should be checked annually using the built-in monitoring system.

a. Monthly - The inspection is visual and is performed on all accessible surfaces of the HEMP barrier. This inspection can be performed in conjunction with other maintenance activities or as a separate activity. Inspect all accessible surfaces of the shield including ceiling areas, all special areas such as the PEA, special protective barriers, and expansion joints. The shield surface should be continuous, without excessive rust or corrosion, without cracks or other breaks, and without any unauthorized penetrations. Excessive rust must be removed, and the shield must be repainted in accordance with the applicable corrective maintenance procedure. Cracks or other

breaks in the shield continuity must be repaired in accordance with the appropriate corrective maintenance procedure. Any unauthorized penetrations must be removed.

b. Annually – The performance of the shield should be checked with the built-in monitoring system. The procedure must precisely define the shield surface areas to be surveyed for each excitation condition. Readings should be compared to the baseline measurements, which were acquired after successful verification testing, and to the previous data set. Any reading that indicates a significant decrease in the shield attenuation should be investigated by visual inspection, portable SELDS instruments, and other means. Shield defects, if found, should be repaired by welding or brazing in accordance with the applicable corrective maintenance procedure.

c. Other – The shield should be inspected using the monthly PMI procedure or tested using the annual procedure if events with potentially adverse effects on shield performance occur. Such events include earthquakes, building settling, accidental collisions with the shield, and extreme temperature excursions.

20.3.5.2 Shielded door assemblies. There is no standard method for inspecting or for performing preventive maintenance on rf shielded doors. Each door type and each manufacturer has a different maintenance procedure. It should be stressed that both the PMI and corrective maintenance procedures must be written specifically for the particular doors used. For example, on some doors, the gasket surfaces must be lubricated. On others, the gasket surfaces must not be lubricated. On some door assemblies, the hinges are adjustable, while on others they are not. And finally, some doors do not have a knife edge and some doors are not equipped with fingerstock.

For illustrative purposes, a PMI procedure is defined in the following paragraphs for one type of door furnished by one door manufacturer. Others will vary from this example.

Tools to be used include a socket wrench or a speed wrench, normal hand tools, a high intensity light for inspection purposes, and a torque wrench. Supplies include cotton swabs, abrasive pads, clean cloths, replacement fingerstock (both inside and outside rows), silicone lubricant spray, alcohol, 4.8 mm (0.19 in) rf gasket material, and gear grease.

Perform the following preventive maintenance activities at the time intervals indicated. Perform the indicated maintenance to correct any discrepancies.

a. General maintenance instructions – The shield doors are adjusted at the manufacturing plant and no hinge adjustments are required. The ball bearings in the hinge assemblies are factory sealed and greased. Cleaning requirements for the door fingerstock and knife edge are addressed in the monthly activities.

Door handles will move through 180 degrees of rotation. Although the rf seal is made after 100-120 degrees of rotation, the door is not fully latched until 180 degrees of rotation is reached. While the sill is strong enough to be stepped upon, the practice should be discouraged as dirt and scratches will degrade the shielding effectiveness. The sill must be protected by a ramp if equipment is rolled across the threshold on a cart or a dolly.

b. Monthly - Inspect fingerstock for dirt and missing or damaged segments. Replace the fingerstock if fingers or sections are missing or damaged. Inspect sealing surfaces for dirt, corrosion or other foreign substances. Clean with a cloth dampened with alcohol and abrasive pads. Spray the knife edge with silicone lubricant.

Examine the latch hardware; tighten loose bolts. Torque bolts to the specified values. Inspect doors for alignment in the frames and for other damage. There should be a uniform gap between the door and door frame. Operate the doors to ensure smooth operation of the door and hinges. If repairs are necessary, repair in accordance with appropriate corrective maintenance procedures.

Test the door interlock system by opening and closing each door and attempting to open the interlocked door. There is no other preventive maintenance on this particular interlock system. Inspect and perform maintenance on the entryway shield in accordance with the PMI covering the HEMP shield.

The alarm circuit should be tested by holding the knob on the digital access control box. After the door is allowed to remain open longer than the prescribed time, an alarm should sound. If the alarm fails to sound, refer to the appropriate corrective maintenance procedure.

c. Quarterly – Check shielding effectiveness of the rf door assembly using portable SELDS instruments. Perform cleaning, alignment adjustments, or repairs in accordance with the applicable PMI or corrective maintenance procedure, if excessive leakage is measured.

d. Annually - Pull the fingerstock lock from the groove and remove all fingerstock. Clean the knife edge and channel contact surfaces using nonmetallic, abrasive pads. Smooth rough surfaces. Replace all fingerstock. Remove the handles from outside. Clean the shaft and handle sleeve, and lubricate with grease. Replace 4.8 mm (0.19 in) rf gasket sealing material on the outside of the door. Reassemble the handle, and tighten firmly.

e. Other – In the event of damage, repair the shielded door in accordance with the corrective maintenance procedure.

20.3.5.3 Shielded access covers. Welded or brazed shielded covers on equipment access ports through the electromagnetic shield should be inspected monthly and tested annually. The PMI procedure is the same as that used for the HEMP shield. If the cover is removed and replaced, shielding effectiveness should be checked in accordance with requirements of the reinstallation procedure.

Shielded equipment access covers with rf-gasketed and bolted seals should be maintained and inspected as follows:

a. Monthly-Inspect for corrosion and general condition in accordance with the HEMP shield PMI. Check that all bolts are in place and at least hand-tight.

b. Quarterly - Check shielding effectiveness with the built-in monitoring system or portable SELDS instruments. Retorque bolts to the specified values if leakage is detected. If the leakage is not corrected by this action, remove the cover, replace the gasket, and clean all sealing surfaces in accordance with the corrective maintenance procedure.

c. Other – Replace the gasket and retorque the bolts whenever the covel is removed and replaced. Check the shielding effectiveness in 'accordance with the reinstallation procedure.

20.3.5.4 Piping WBC penetration protection, All welded and brazed joints on piping WBC protective devices should be inspected fo, corrosion, cracks, and general condition at least annually. More frequent inspection should be performed on piping penetrations where condensation occurs. Weld defects should be repaired in accordance with the weld repair procedure. Rust and corrosion should be removed and the WBC should be repainted in accordance with the applicable corrective maintenance procedure.

20.3.5.5 Ventilation and fiber optic WBC penetration protective devices. The preventive maintenance and inspection requirements fo, ventilation WBC array panels depend upon the type of construction. WBCs constructed using commercial honeycomb material are less durable and require greater maintenance attention. The following PMI procedures should be established.

a. Monthly – Monthly inspections are made to ensure that no conductors have been inserted through the WBC. Unfortunately, a WBC is a convenient penetration through which to feed a conductor, such as a television antenna, into the building. For honeycomb WBCs, the inspection should include assessing integrity of the honeycomb and its connections to its frame. Check also to see that there are no signs of corrosion or

weld cracks. Any unauthorized iterms in the WBC must be removed. If any defects exist, repair in accordance with a specified corrective maintenance procedure.

b. Quarterly - Check shielding effectiveness of honeycomb WBC arrays with the built-in monitoring system or portable SELDS instruments. Repair or replace the WBC panel in accordance with the applicable corrective maintenance procedure if leakage is found.

c. Annually – Check the performance of all ventilation and fiber optic WBC penetration protection devices with the built-in monitoring system. These measurements are performed as part of the annual HEMP shield PMI. Defects must be repaired as necessary.

No special tools are required for these PMIs, except ladders as needed for viewing the WBCs.

20.3.5.6 Filter/ESA assemblies. Experience at some facilities has shown that filter/ESA enclosures are subject to damage when the cover screws are removed and reinstalled. Either the screws bind and break, or the mating threads on the enclosure are easily stripped. Under these conditions, regular inspections of the filters may result in more damage than they prevent. When filter/ESA assemblies are developed and installed in accordance with the maintainability and human engineering requirements of MIL-STD-188-125, these inspection problems should not occur. Nevertheless, the enclosures should be opened only when necessary for PMIs or corrective maintenance.

Perform the following filter/ESA preventive maintenance and inspections activities at the time intervals indicated. Perform the indicated maintenance to correct any discrepancies.

a. Monthly - Visually inspect each filter/ESA assembly cover to verify that the installation is intact and that there is no evidence of damage, moisture, or unauthorized conductors entering the enclosure. All bolts and fasteners holding the cover should be securely in place. The cover gasket should be uniformly compressed to approximately 3.2 mm (0.125 in) or as specified. If defects are indicated, the biannual procedure should be performed. Check installation welds for corrosion, cracking, and general condition, and perform repairs as necessary.

b. Annually - Check shielding effectiveness in the area of the protected electrical POE. These checks are performed using the built-in monitoring system as part of the HEMP shield annual PMI.

c. Biannually - Remove the cover of each filter enclosure. Inspect each filter element case. The cases should show no damage, bulging, leakage, or discoloration. Feel the filter case; excessive temperature may indicate a problem with the filter. If any of these problems are found, the affected filter must be replaced. Replace with an identical unit in accordance with the specified corrective maintenance procedure. In no case should the filter be bypassed. Inspect each external bleeder resistor. If damaged or charred, replace the component.

   Inspect each ESA. The case should show no signs of damage, bulging, discoloration, or charring. If any one of these conditions is present, replace the ESA with an identical type. The leads to the ESA should be as short as possible.

d. Other – Failure of filters and ESAs may be detected operationally. If the circuit breakers on the protected line trip, the filter/ESA assembly should be inspected using the biannual PMI procedure.

Although the internal examination of each assembly is required biannually, the filter/ESA inspections should be performed on a continuous basis. An inspection schedule indicating when each assembly is to be opened should be prepared. Devices with similar functions should be inspected at different times. If there are two heat exchangers, for example, the filter/ESA assembly for the first unit should be inspected in one year and those for the second should be inspected in the next year. If a problem is found with a particular type of filter or ESA, all other devices of the same type should then be immediately inspected.

The biannual inspection of a filter/ESA assembly should be performed whenever it is necessary to open the enclosure for other reasons. Future inspections should be rescheduled appropriately.

The internal inspection of filter/ESAs is intended to be performed with power on, in accordance with safety precautions that must be included in the PMI procedure. If local regulations require power off for these inspections, such regulations should be written into the procedure and observed.

20.3.5.7 Conduit penetrations. Shielded conduits are visually inspected on an annual basis. The only tools required are adequate lighting, a magnifying glass, a pick, and a wire brush. Conduits that are buried or otherwise inaccessible are inspected only when they become exposed, or when inspections in accessible areas have uncovered some generic defects.

a. Annually – Perform a visual inspection of all exposed HEMP shielded conduits. Verify that there are no cracks or voids in the circumferential weld at joints or the point where the conduit penetrates the shield. If a crack or void is found, repair in accordance with the specified corrective maintenance procedure. If rust is seen at the conduit joint, clean off the rust and inspect for cracks or voids. If a crack or void is found, perform the specified corrective maintenance. Rust should be removed with a wire brush. The cleaned surface should be painted in accordance with the drawings. If water intrusion is found in a conduit, the source of the intrusion should be located and the conduit should be repaired in accordance with the specified repair procedure.

b. Other - Inspect in accordance with annual procedure if there is physical damage, freeze damage, water intrusion, or severe ground motion.

20.3.5.8 Shielded enclosures. Shielded enclosures with rf-gasketed and bolted covers should be inspected monthly for corrosion, damage, and general condition. All bolts and fasteners should be in place and at least hand-tight. Annual inspections of the interior should also be performed.

a. Monthly – Visually inspect each enclosure cover to verify that the installation is intact and that there is no evidence of damage or moisture. All bolts holding the cover should be in place and securely fastened. The cover gasket should be uniformly compressed to approximately 3.2 mm (0.125 in). All conduit connections should be properly made. If any problems are noted, perform annual PMI activities.

b. Annually - Remove the bolts. Open the cover. Inspect the gasket for signs of damage or permanent set. Inspect the rf mating surfaces for signs of contamination, corrosion or rust. Clean with a wire brush and/or a cleaning solvent. If any connectors are damaged, replace in accordance with the appropriate repair procedure. If the gasket is damaged, it must be replaced. If the mating surfaces need replating, replate in accordance with the specified corrective maintenance procedure.

Replace cover and secure the cover bolts. All bolts/screws holding the cover must be in place. The cover gasket must be uniformly compressed to approximately 3.2 mm (0.125 in) or as specified for the gasket design.

c. Other – Whenever an enclosure is accessed for other reasons, all annual PMI activities should be performed. Also, these activities should be performed following reports of damage or moisture intrusion.

20.3.5.9 Special protective measures. Procedures for preventive maintenance and inspection should be prepared for all SPMs, as required for the particular design.

20.3.5.10 PMI schedule. A schedule is prepared to show when each PMI is to be performed. The HEMP protection PMI schedule should be integrated with the maintenance schedules for other subsystems at the facility. This simplifies the scheduling process and reduces the administrative burden on site maintenance personnel.

In the previous paragraphs, information was given on how frequently PMIs should be scheduled. This schedule information should be used only as initial guidance. If experience-based information is available regarding maintenance intervals for the particular HCIs at a given facility, that information should be used. As results are obtained from the performance of PMI activities, that information should be evaluated and used as the basis for revising the schedule. If no problems are noted for a given HCI inspected at a particular schedule interval, consideration may be give to lengthening the interval between inspections. If problems are always found, the inspection interval should be shortened.

20.3.5.11 PMI manpower. There are no requirements for highly specialized HEMP personnel in the performance of the various PMI activities. Typical electrical/mechanical maintenance technicians with a modest amount of HEMP training can be used for most maintenance. For specialized devices such as communication system HCIs, the electronics technicians assigned to the site or facility can be used. PMI documentation and a reasonable level of training are necessary before maintenance personnel can be expected to perform these activities.

Hardness preventive maintenance and inspections at a facility should have no significant impact on manning. The performance of each procedure is not very labor intensive. Their frequency of occurrence is relatively low. Some procedures may require two persons, either for safety considerations or for support purposes.

Experience from the facilities where HM/HS has been successfully conducted indicates that most military personnel can be trained to conduct HEMP PMI procedures.

20.3.6 Corrective maintenance. The second type of hardness maintenance activity is corrective maintenance. Corrective maintenance is performed in response to the identification of anomalies or defects uncovered during the performance of PMI activities and hardness surveillance tests. Observations during normal operation can also identify problems and cause corrective maintenance actions to be initiated. Unlike the first class of activities, these activities are performed only as needed, not periodically. Corrective maintenance includes repair actions that must be accomplished to bring the hardness critical item or assembly to a satisfactory operational condition.

An HCI operating in an unsatisfactory manner can result in MEE becoming vulnerable to HEMP. This vulnerability remains through the period of time that the HCI is in need of repair or replacement. Vulnerability to HEMP means that the HCI, operating in an unsatisfactory manner, may cause the mission to fail if a HEMP event happens.

Upon completion of a repair procedure, including specified testing, the affected HCI is considered to be brought back to an acceptable state. No requirement exists for conducting the related PMI procedure. The normal PMI schedule is resumed upon completion of the corrective maintenance activity.

20.3.6.1 Required corrective maintenance procedures. Corrective maintenance procedures are prepared for the specific hardness critical elements at a particular facility. General procedures have limited value. Required corrective maintenance procedures typically include the following:

a. Weld repair procedures for the HEMP shield and for installation of POE protective devices

b. Repainting and corrosion protection procedures for the HEMP shield and POE protective devices

c. Alignment procedures for rf shielded doors

d. Repair/replacement procedures for shielded doors

e. Removal/reinstallation/repair/replacement procedures for shielded access covers

f. Repair/replacement procedures for piping WBCs, welded ventilation WBC panels, honeycomb WBC panels, and fiber optic WBCs

g. Replacement procedures for filters and ESAs

h. Gasket replacement procedures

i. Replating procedures for rf mating surfaces

j. Conduit weld repair procedures

k. Repair and replacement procedures for SPMs, as required

Many of the repairs to a MIL-STD-188-125 hardened facility will involve cutting and welding operations. Care must be exercised to ensure that sensitive systems are not damaged when performing these actions. For example, the penetrating cables must normally be removed when repairing a fiber optic WBC or a shielded conduit.

20.3.6.2 Corrective maintenance procedure example. The corrective maintenance procedure should contain certain information. An example of this information is presented as an outline of the required sections.

a. Objective – describes the goal of the procedure.

b. Application – lists the HCIs addressed by the corrective maintenance procedure.

c. Notes – provides specific comments relevant to the repair.

d. References – identifies figures, drawings and other references applicable to the corrective maintenance procedure.

e. Personnel requirements - defines the number and type of maintenance personnel required to accomplish the task.

f. Time required - specifies the personnel hours required for preparation/travel and for actually accomplishing the repair.

g. Safety – provides special safety requirements. Appropriate site safety procedures are to be observed.

h. Security – provides special security procedures which must be observed.

i. Tools – lists special tools required for the corrective maintenance procedure.

j. Supplies – lists supplies which are needed for the performance of the corrective maintenance procedure.

k. Instructions – provides the instructions for performing the corrective maintenance.

l. Test requirements – identifies testing, including factory tests, to be performed to verify that components perform acceptably and that the repair has been properly made.

A sample corrective maintenance procedure is illustrated in figure 185.

On-site HEMP testing capability will normally be limited to shield performance checks using the built-in monitoring system and portable SELDS instruments. Other types of testing must be obtained from an outside agency or contractor.

CM-4 Clean/Replace Hardness-Critical Air Line Filters

OBJECTIVE:

This corrective maintenance procedure covers the replacement and cleaning of airline filters necessary to generate air pressure needed to inflate the pneumatic bladder that maintains electrical contact on rf shielded pneumatic doors.

APPLICATION :

This procedure covers the air line filters used in rf shielded sliding doors with a pneumatic bladder to maintain electrical contact.

NOTES:

This procedure was written for a generalized pneumatic door. The procedure may require modification depending on the characteristics of the specific door to be repaired.

REFERENCES: Manufacturer' s instruction manual for the sliding (pneumatic) shielded door

PERSONNEL REQUIREMENTS: 1 maintenance technician, skill level 5

TIME REQUIRED (hours):

PREPARATION 1.0

ACTIVITIES 2.0

SAFETY:

No special hazards are involved. Normal site safety requirements are to be observed.

SECURITY:

Normal site security requirements, access requirements. and procedures are to be observed. Special authorization may be required to keep the door open for time period specified above.

FIGURE 185. Sample corrective maintenance procedure.

TOOLS:

Flashlight	Socket, speed wrench kit
Door sill protector	2-m step ladder
Magnifying glass	

SUPPLIES: Maintenance kit, replacement air line filters

INSTRUCTIONS:

1. The instructions contained here are for a general pneumatic door; documentation from the manufacturer should be consulted for specific instructions on the door to be maintained.
2. The threshold of shielded doors, both pneumatic and fingerstock doors, contain contact surfaces needed to maintain shielding integrity. In general, personnel should not step or stand on these surfaces.
3. It is recommended that a heavy-duty drop cloth be placed on the floor prior to servicing the door to protect floor finishes.
4. The air line filters remove moisture from the air lines and should be inspected and drained periodically.
5. To replace contaminated filters, remove (unscrew) glass bowls from main control panel. Replace filter cartridge in each bowl. Consult manufacturer for specific filter type and part number.
6. Note that contamination in the secondary filter indicates that the elements in both the primary and secondary filters need replacing.

TESTING:

1. Perform SELDS testing following replacement of air line filter elements to verify pneumatic bladder is properly inflated when door is closed. The entire circumference of the door seal should be checked using the procedure in the SELDS operations manual.

FIGURE 185. Sample corrective maintenance procedure (continued).

20.3.6.3 Corrective maintenance manpower requirements. The performance of many of the repair activities requires a particular skill level reflective of the activity undertaken. For example, MIG welding is performed by an experienced MIG welder. It is not anticipated that there will be a significant manpower requirement for the performance of corrective maintenance activities in a facility designed and constructed to the requirements of MIL-STD-188-125.

20.3.7 Periodic hardness surveillance/reverification testing. The hardness surveillance inspections and measurements that do not require significant HEMP expertise or an extensive inventory of special HEMP test equipment can be performed by site personnel and have been included in the PMI procedures. However, these activities generally provide only qualitative information regarding the performance of the HEMP protection subsystem. Data to support quantitative assessment of the facility HEMP hardness and survivability are also required periodically during the operational phase. The testing to acquire such data is designated as hardness surveillance/reverification testing.

One of the purposes of periodic hardness surveillance/reverification testing is to measure the impacts on HEMP protection subsystem performance from aging and use. This information is used to establish quantitative degradation rates for the various types of HCIs.

A second purpose is to perform an evaluation of effectiveness of the total HM/HS program including PMIs, repair procedures, configuration management, logistics, and training. If performance of the HEMP protection is found to be below acceptable levels, the HM/HS program must be modified to prevent future recurrences of the same problems.

The third surveillance/reverification test objective is to verify that the HEMP hardness has not been adversely affected by minor facility changes and retrofits performed subsequent to the previous test.

To meet these objectives, data from the periodic surveillance/reverification test must be relatable to the MIL-STD-188-125 acceptance and hardness verification tests. The test sequence must include overall barrier performance measurements and transient suppression/attenuation measurements on the electrical POE protective devices. Since these tests involve use of high-level simulators and special data acquisition systems and the interpretation of results requires HEMP expertise that is not normally available on site, hardness surveillance/reverification testing is performed by an outside agency or contractor.

20.3.7.1 Frequency of testing. Hardness surveillance/reverification tests are recommended at five- to seven-year intervals throughout the operational life of a HEMP-protected facility.

20.3.7.2 Hardness surveillance survey. Inspection of the HEMP protection subsystem by an independent, outside party can often detect problems that may be inadvertently overlooked on a daily basis by the operators and maintainers. Therefore, as part of each hardness surveillance/reverification test sequence, the site HEMP protection should be thoroughly surveyed by an experienced staff member from the organization that will perform the testing.

The survey should be conducted approximately six months before the start of testing. This scheduling provides sufficient time to correct the known and observed deficiencies before the measurements are taken.

The survey visit should also serve as the initial coordination meeting between site personnel and the testing organization. Site records should be reviewed to identify changes to the HEMP protection subsystem and suite of MEE since the preceding test program. Results of the preceding test should also be examined, and necessary information for test planning should be obtained.

20.3.7.3 Test documentation. A test plan and detailed procedures must be prepared for the hardness surveillance/reverification test program and must be coordinated with the site personnel. Test results are also required to be documented in a test report and to be provided to the site.

Surveillance/reverification test documentation should meet the same requirements as verification test plans and reports. Detailed outlines are provided in section 21.

20.3.7.4 Surveillance/reverification test requirements.

20.3.7.4.1 Barrier effectiveness testing. As previously mentioned, the surveillance/reverification test sequence must include measurements to evaluate the overall effective ness of the HEMP electromagnetic barrier. This information is required to reconfirm the basic premise that HEMP-induced stresses in the protected volume are bounded by the maximum allowable residual internal stresses from pulsed current injection testing.

The barrier overall effectiveness testing may be performed using the built-in monitoring system, cw immersion, shielding effectiveness measurements, or portable SELDS

measurements, as determined by the responsible service. These test methods are described in section 16.

20.3.7.4.2 Pulsed current injection. It is recommended that 100 percent of filter/ ESA assemblies on penetrating electrical conductors be PCI tested during the hardness surveillance/reverification sequence. These tests should be performed in accordance with PCI verification procedures of appendix B to MIL-STD-188-125 and guidance in section 16.

The basis for recommending full PCI testing is that these tests provide the most realistic simulation of a reasonable worst case HEMP event. Since internal configuration controls are minimal and no other checks of C-E equipment vulnerability thresholds are required, sample testing does not provide adequate data for formulating a hardness statement.

20.3.7.4.3 Tests of special protective measures. Verification testing of SPMs used to protect mission-critical systems requires both coupling measurements and cable current injection. Unless significant changes to the coupling configuration have occurred, it is not necessary to repeat the coupling measurements during hardness surveillance/reverification testing. However, the PCI testing on cables should be performed as part of the HS test.

20.3.8 Training. Training is essential to the HM/HS program. Most hardness maintenance and inspection procedures can be accomplished with the skill levels available in a typical C^4I facility organization. However, maintenance personnel must be trained to perform the procedures.

A hardness training program should be developed to serve a variety of purposes. Hardness awareness briefings should be given to all site personnel to ensure a sufficient level of knowledge of hardness concerns. More advanced hardness training courses should be provided to the HM/HS personnel.

Site personnel must have a practical understanding of HEMP phenomena and HEMP protection methods if they are to appreciate why certain things are done in a particular way to preserve HEMP protection. A useful approach to satisfy the HEMP training needs is to develop and offer two courses. These courses are provided in addition to other classroom and on-the-job training required by the facility operators and maintenance personnel.

The subject of the first course is HEMP awareness. The presentation should be designed for a length of two to four hours. It should include an overview of the HEMP threat and the potential effects on the operation of communication-electronic systems. The principles and practices of HEMP protection should be introduced. The importance

of HEMP survivability to the site mission and the role of each individual in preserving the hardness should be emphasized. A suggested course outline is given in table XXII. The awareness training should be presented at an unclassified level to all personnel associated with the facility, immediately after their arrival on site.

The second course, for maintenance personnel, should be designed with 12 to 16 hours of classroom work and additional on-the-job training for a period of one to two weeks. Information on HEMP phenomena and protection principles should be provided in somewhat greater detail. As indicated in the outline in table XXIII, however, the emphasis of this course is hardness maintenance and surveillance for the HEMP protective measures. The HM/HS requirements and procedures should be discussed in the classroom. On-the-job training then provides the maintenance personnel with the hands-on experience necessary for performing the maintenance and inspection activities. This course may be classified or unclassified, as needed. In either case, the trainees must become familiar with the classification guidance regarding the presence of defective HCIs at the facility.

Both of the courses should be given at regular intervals. The courses can most effectively be presented either by means of professionally prepared video tapes or by using a qualified HEMP instructor employing visual aids and workbooks. Training resources are being developed by the services and by DNA, and the centers of HEMP expertise should be contacted to determine availability of curricula and materials.

An effective way to provide pertinent information for initial operation of the facility and to provide source material for the HM/HS courses is to require the developer of the HM/HS plan or the HEMP protection subsystem contractor to train Government personnel as part of the contract.

20.4 References.

20-1. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions," MIL-STD-188-125 (effective), Dept. of Defense, Washington, DC.

20-2. "Military Standard – Engineering Drawing Practices," MIL-STD-100 (effective), Dept. of Defense, Washington, DC.

20-3. Shockley, J. W., "High-Altitude Electromagnetic Pulse (HEMP) Hardness Maintenance/Hardness Surveillance Manual for HEMP Shielding Protection," DNA-TR-91-87, Defense Nuclear Agency, Washington, DC.

TABLE XXII. HEMP awareness training.

HEMP AWARENESS COURSE OUTLINE
I. Introduction
A. Purpose of course
B. Goals of course
II. HEMP phenomena
A. Generation
B. Threat
C. Facility mission implications
III. Mission implications
A. Site implications
B. Security requirements
C. Headquarters requirements
IV. HEMP protection
A. Techniques
B. Maintenance
C. Constraints and limitations
D. Documentation procedures
V. Summary
A. Major points
B. Effects on personnel

TABLE XXIII. Maintenance personnel training.

HEMP MAINTENANCE COURSE OUTLINE

I. Tutorial

- A. Introduction
- B. HEMP protection principles
- C. Facility HEMP protection
- D. HM/HS program
- E. Hardness critical items
- F. Preventive maintenance
- G. Corrective maintenance
- H. Hardness surveillance
- I. Documentation and reporting
- J. Security and safety
- K. Tools, supplies and test equipment
- L. Spares/replacement parts
- M. Configuration control

II. On-the-job training

- A. Introduction
- B. PMI procedures
- C. Troubleshooting and repair procedures
- D. Hardness surveillance/ reverification testing

21. HEMP PROGRAM MANAGEMENT

21.1 Basic principles. This handbook section addresses management of the HEMP protection program for a fixed, ground-based C⁴I site. The technology for the development, demonstration, and long-term preservation of facility hardness is generally known and proven in service to be effective, but its implementation requires meticulous attention to details. As required for any program with this level of complexity, the efforts of many agencies and individuals need to be integrated across disciplinary boundaries and throughout the various phases of acquisition and deployment. This is the role of the individual or individuals with overall responsibility for ensuring HEMP hardness. Throughout the handbook, this position is denoted as the "HEMP program manager."

This section recommends that responsibility for HEMP program management for the entire acquisition sequence be assigned to a single individual, and it is written under this assumption. However, both the title of the position and the task assignments are at the discretion of the individual services.

21.1.1 The HEMP program 'manager. There are likely to be numerous HEMP "managers" during the life cycle of a hardened facility. The requiring command will often have a survivability staff and will assign an individual from this office to define the site operational hardness requirements. The design agent—usually the U.S. Army Corps of Engineers (USACE), Naval Facilities Engineering Command (NAVFACENGCOM), or General Services Administration—and the design contractor may also delegate primary responsibility for the HEMP protection to a particular staff member. Similarly, focal points for HEMP hardness may be established by organizations of the construction, equipment installation, and verification test teams. Finally, a primary point of contact for HEMP will normally be designated after the facility begins operations. Each of these managers has prescribed responsibilities for a particular part of a total HEMP program.

It is recommended that a single Government point of contact be designated as the "HEMP program manager" for the entire acquisition program—from the start of the planning, programming, and budgeting phase through the completion of verification. Assignment to this position will vary between services and possibly between projects. Selection of the HEMP program manager from the using organization (mission resource) is an option that should be considered.

The job of the HEMP program manager during the acquisition phases is to ensure that the facility is planned, designed, built, and tested to provide the operationally required HEMP survivability and that it is delivered with the tools (documentation; procedures;

spares, supplies, and special tools and test equipment; training materials; etc.) necessary to maintain the desired hardness. The HEMP program manger accomplishes these objectives through careful planning, integration, and supervision. The purpose of this section is to assist the HEMP program manager by identifying tasks and providing guidelines on how and when they should be done. Much of the information presented here has been adapted from reference 21–1, a handbook for managing nuclear survivability programs for developmental equipment.

In many cases, the HEMP program manager simply verifies that essential HEMP tasks have been assigned to one of the various "managers" described in the first paragraph of this subsection and reviews the products for quality and completeness. The HEMP program manager may elect to personally supervise or perform some program activities. Successful performance of HEMP program management duties requires a considerable amount of HEMP knowledge and experience. As needed, therefore, technical support from other service organizations, the Defense Nuclear Agency, and contractors should be obtained.

As site operators and maintenance personnel assume responsibility for other facility subsystems, management of the HEMP protection should also begin to transition and the transfer should be complete by the end of verification. The HEMP program manager for the operations and support (O&S) phase is recommended to be a designated subordinate of the site commander. The job at this time in the life cycle is to ensure that the HEMP hardening is operated and maintained at the highest possible state of operational readiness.

21.1.2 The facility life cycle. HEMP program management activities during the life cycle of a newly constructed, hardened facility will be discussed here in a sequence of six phases. As used in MIL-STD-188-125 (reference 21–2), the term "facility" is a building or other structure, either fixed or transportable in nature, with its utilities, ground networks, and electrical supporting structures. All wiring and cabling and electrical and electronic equipment are also considered to be part of the facility. This sequence, illustrated in figure 186, is a composite of military construction program (MCP) procedures (reference 21–3), regulations for major system acquisitions (references 21-4 and 21–5), and HEMP-unique requirements of MIL-STD-188-125. Although a new construction example is used, virtually the same elements will occur in the case of a major hardening retrofit.

Names assigned to the six phases reflect the principal activities occurring during that period of time. Every acquisition phase, however, includes elements of preparation for future events. Although the hardness verification test is the fifth block, for example, the test approach is determined during planning, programming, and budgeting, and test plan

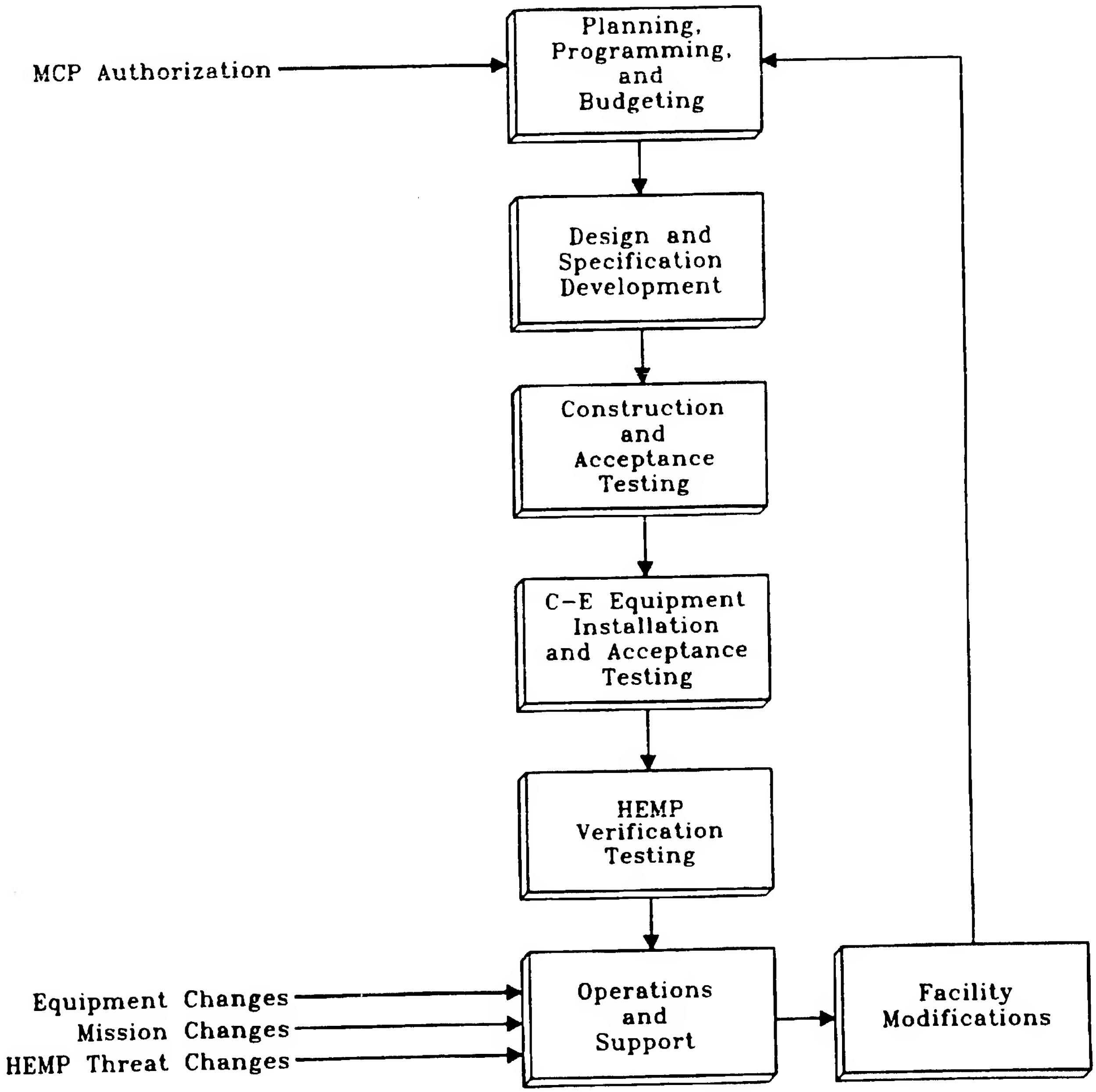


FIGURE 186. Hardened facility life cycle diagram.

preparation starts during design and specification development. Similarly, planning for HM and HS takes place during all of the acquisition stages.

The need for a new facility, the C4I missions and basic equipment suite, and the nuclear survivability requirements are determined in the planning, programming, and budgeting phase. New systems and equipment, if required by the validated and approved Mission Need Statement, are developed in accordance with references 21–4 and 21-5. New buildings are acquired through the MCP process. A facility requirements document, which will serve as the guide for building designers, is prepared. Cost estimates for the proposed program, from design through O&S, are developed and submitted. If the MCP project is authorized and the supporting budgets are approved, design activity is initiated.

The principal products of the design phase are detailed drawings and specifications for the building construction. The facility HEMP shield and all or nearly all of the POE protective devices and special protective measures will normally be included in these packages. In the same time frame, planning for the C-E equipment installation, the verification test, and site O&S should be commenced.

The building and the majority of the HEMP hardening are constructed during the third phase. Hardness assurance occurs in parallel with the fabrication effort, and acceptance tests required by MIL-STD-188-125 are performed near the conclusion of the phase. All preparations for installing the C-E hardware must be completed prior to acceptance. Furthermore, at least a preliminary HM/HS program (for HCIs provided under the construction contract) should be established.

Hardness maintenance and hardness surveillance include preventive maintenance performed on the HEMP protection subsystem, inspections and tests, repairs, and the other activities required to preserve the HEMP survivability. Thus, the HM/HS planning efforts that occur during design, construction, and equipment installation must include all of the following:

a. Development of the HEMP protection subsystem documentation, including operating and maintenance procedures

b. Provisioning with spares/repair parts/supplies/special tools/special test equipment

c. Development of the configuration management plan and implemental ion of procedures for controlling changes to the design baseline

d. Preserving all hardness assurance, acceptance, and verification test results as baseline performance data

Reference 21-6 provides guidance for HM/HS planning and is also useful in planning the hardness assurance program.

The C-E equipment is then installed and checked out. This activity may include additions and modifications to the HEMP protection subsystem and, if so, it will also include the same QA and acceptance elements as construction. During this phase, the verification test plan and final HM/HS program must be completed.

The operators and maintenance personnel of the site O&S staff arrive during the C-E equipment installation phase. They should be trained and should assume responsibility for HM and HS on HCIs supplied under the construction contract. After equipment checkout is completed, initial operating capability occurs and mission operations can begin.

Hardness verification test requirements in MIL-STD-188-125 were designed to limit the degree of interference with facility functions, so that testing can be performed in parallel with mission operations. Findings of the measurement program will be documented in a formal test report. If deficiencies are found in the HEMP protection, appropriate repairs, modifications, and subsequent retesting efforts are initiated.

Fully normal operations and maintenance now begin and continue through the end of life. Use and maintenance of the HEMP protection subsystem occurs in accordance with the HM/HS program. Change is a fact of life at most facilities, however, and continuous attention is required to preserve hardness through mission changes, MEE changes, and threat changes.

21.1.3 Facility acquisition organization. Specific agencies participating in the facility acquisition will vary from military service to military service and, also, from project to project. Certain tasks are fundamental to the process, however, and the generic organization for accomplishing these functions can be described. The major participants in this organization are as follows:

a. Requiring command – the command that identifies the need for a new facility to perform its assigned mission. Each command continually reevaluates its operational needs and assesses resources necessary for accomplishing the mission. When a new facility is found to be the best approach, the requiring command defines essential facility features and initiates the MCP and related acquisition requests. The requiring command will generally participate in reviews during the acquisition cycle.

b. Approving authority – The person who evaluates all requests, assigns priorities to competing projects, and seeks MCP authorizations and budget approvals. Direction to proceed with approved programs is issued by the approving authority.

c. Host command - the command responsible for the base on which the new facility will be situated. Involvement of the host command arises from the base support services which it must provide. The host command will also generally be a participant in the various reviews.

d. Supporting command for HEMP logistics - the organization with primary responsibility for preparing the HM/HS program. It may be an activity specifically chartered for HM/HS program development, or one of the other participating organizations may be assigned to perform this task.

e. Design agent - usually, the U.S. Army Corps of Engineers or Naval Facilities Engineering Command. The design agent is responsible for providing a facility design that meets the needs of the requiring command and can be constructed within the allocated cost constraints. The design may be done "in-house, " or an architect-engineer may be hired.

f. Construction agent – responsible for constructing the building in accordance with the approved design drawings and specifications. The construction agent supervises the work of the construction contractor.

g. Installing command - the activity (or activities) that plans and performs the C-E equipment installation. The installing command provides inputs to ensure compatibility between the facility design and equipment requirements and acquires information so that the installation plan will be consistent with the building configuration. In multiple-use facilities, there may be more than a single installing command and they may be from DoD components other than the service for which the facility is being constructed.

h. Verification test organization – the agency that plans and performs the hardness verification program. The verification test organization participates principally to obtain test planning information, but may be able to provide assistance in meeting testability specifications.

The principal responsibilities of the design agent (and design contractor, if applicable) are fulfilled when the building design has been accepted, although some participation in a construction surveillance role may continue. The construction agent is then designated[11] and assumes the primary responsibility for the construction phase. Participation of the construction agent and the successful construction contractor end when the building is accepted and all construction phase deficiencies are satisfactorily corrected.

[11]The design agent and construction agent may be from the same USACE or NAVFACENGCOM division, and they may be the same individual.

Involvements of the installing command and verification test organization continue until their respective tasks are completed.

21.1.4 Military service differences. Each service has its own instructions, procedures, and organizations for the implementation of DoD acquisition policies. The descriptions of these department-unique elements are beyond this handbook's scope. However, table XXIV provides selected information for establishing the correlation between the generic organization and processes presented here and those which will exist for actual projects of three DoD departments.

21.2 MIL-STD-188-125 requirements. 12

4.2 Hardness program management. Hardness program manage ment[2] for fixed and transportable ground-based facilities being HEMP hardened in accordance with requirements of this standard shall implement the policy and procedures of Department of Defense Directive 5000.1 and DoD instruction 5000.2. Design and engineering, fabrication, installation, and testing activities shall be managed to accomplish the following objectives:

a. To provide a HEMP-protected facility design based upon verifiable performance specifications

b. To verify hardness levels through a cost-effective program of testing and analysis

c. During the acquisition process, to develop a maintenance and surveillance program which supports the operational phase of life-cycle HEMP hardness

2HEMP planning, analysis, design, test procedures, and test reporting documentation, and requirements for hardness maintenance and hardness surveillance program development and execution are described in MIL-HDBK-429.

MIL-STD-188-125-series documents are technical standards, and detailed requirements do not address management issues. The subject of HEMP program management,

[12]Note that DoD Directive 4245.4 was superseded subsequent to publication of MIL-STD-188-125, and acquisition requirements for nuclear survivable systems have been incorporated into DoD Directive 5000.1 and DoD Instruction 5000.2.

TABLE XXIV. Military Department information relevant to HEMP facility acquisition.

Generic Term / Military Dept.	Army	Navy	Air Force
ORGANIZATION Requiring Command	Any Major Command (MACOM)	Any Major Command (MAJCOM)	Any Major Command (MAJCOM)
Approving Authority	Headquarters, Department of the Army	Chief of Naval Operations	Headquarters, U.S. Air Force
Host Command	Any MACOM	Any MAJCOM	Any MAJCOM
Support Command—HEMP Logistics	Army Materiel Command	Space and Naval Warface Systems Command (SPAWAR); Navy Computer and Tele-communications Command (NAVCOMTELCOM)	Air Force Material Command (AFMC)
Design Agent	USACE	NAVFACENGCOM	USACE or NAVFACENGCOM
Construction Agent	USACE	NAVFACENGCOM	USACE or NAVFACENGCOM
Installing Command	U.S. Army Information Systems Command, U.S. Army Communications Electronics Command	SPAWAR; NAVCOMTELCOM	AFMC
Verification Test Organization	USACE	NAVFACENGCOM	1839 Engineering Installation Group
Centers of HEMP Research and Development Expertise[a]	Army Research Laboratories	Naval Surface Weapons Center	Phillips Laboratory

[a]DNA is the DoD-level center of HEMP expertise.

TABLE XXIV. Military Department information relevant to HEMP facility acquisition (continued).

Generic Term / Military Dept.	Army	Navy	Air Force
Centers of HEMP Construction Expertise	USACE[b]	NAVFACENGCOM[c]	Air Force Civil Engineering Support Agency; Technical Integration Center
FORMAL MCP DOCUMENTATION MCP Project Data	DD Form 1391	DD Form 1391	DD Form 1391
Facility Requirements Document	Project Development Brochure	Base Electronics System Engineering Plan	Requirements and Management Plan
Facility Acceptance	DD Form 1354	DD Form 1354	DD Form 1354
HEMP GUIDANCE	AR 70-60, "Nuclear Survivability" ASR 25-5, "Implementation, Operations, and Maintenance of USAISC High-Altitude Electromagnetic Pulse (HEMP) Hardened Facilities" EP 1110-3-2, "Engineering and Design of EMP and TEMPEST Protection for Facilities"	OPNAV 3410.3, "Nuclear Survivability of Navy and Marine Corps Systems" NAVFAC 11010.44, "Shore Facilities Planning Construction"	AFR 80-38, "Management of the Air Force Survivability Program" ETL, "HEMP Hardening in Facilities" "USAF Handbook for the Design and Construction of HEMP/ TEMPEST and Other Shields in Facilities"

[b]Construction Engineering Research Laboratories; Huntsville Division; and Omaha District.

[c]Naval Civil Engineering Laboratory, Port Hueneme, CA.

particularly as it relates to planning for HM and HS, is considered to be critically important to fielding an effective HEMP protection subsystem. Reference to the guidance in the handbook was therefore provided.

Other provisions of MIL-STD-188-125 related to management include the requirement to document quality assurance, acceptance, and verification test procedures and results. Copies of the test plans and test reports are to be preserved as baseline configuration and performance data. Hardness surveillance results will be compared with these original measurements to evaluate effectiveness of the HM/HS program and to establish quantitative degradation rates for HCIs.

21.3 Planning, programming, and budgeting phase.

21.3.1 Milestones. Formally, the planning, programming, and budgeting (PP&B) system is the process for formulating long-range military capability objectives, acquisition needs, and investment plans and for developing these into inputs to the President's defense budget. References 21–7 and 21–8 describe the system. After budget approval, funding resources are allocated to the DoD components, subordinate organizations, and individual programs.

On the more microscopic scale of the HEMP program manager and this handbook, the PP&B phase of the facility life cycle is considered to start with the requiring command's identification of need for a new HEMP-hardened site (or a major HEMP retrofit). Also, for purposes of this document, the first phase is defined to continue through authorization to proceed with the design, preparation of the HEMP section of the facility requirements document, and development of the HEMP program plan. Significant HEMP program events occurring during this period are indicated in figure 187.

21.3.2 Execution. Throughout the execution of the PP&B phase, as well as in the facility acquisition phases, the HEMP protection subsystem should be recognized as one part of a total system. The HEMP requirements and design must be coordinated and made compatible with the functional requirements of the equipment and requirements of related engineering disciplines. In particular, the HEMP hardening must be integrated with measures specified for other electromagnetic purposes-electromagnetic interference/compatibility, lighting, and TEMPEST—and with those for hardening against other threats.

In many cases, a single component can serve multiple purposes. The HEMP shield and filters, for example, can also be used to provide TEMPEST isolation with only minor changes to the requirements. The shield might also serve as a physical security barrier or

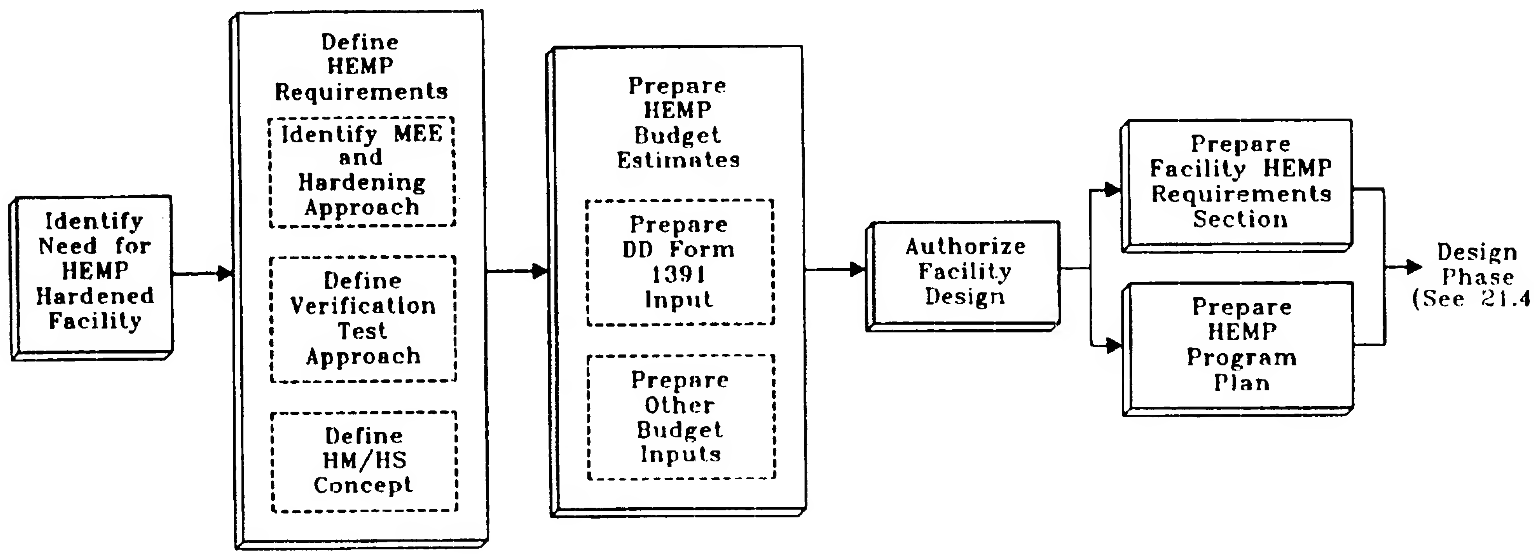


FIGURE 187. **HEMP activities in the PP&B phase.**

a blast span plate. In other situations, conflicts among the requirements of the different disciplines may arise.

The HEMP program manager should confer with those responsible for these related areas to develop a consistent and integrated approach and to resolve any differences. Because of the strong correlation between HEMP hardening measures and physical and electronic security designs, consultation with the cognizant security authority is particularly important.

21.3.2.1 HEMP requirements definition. The initial definition of HEMP hardening requirements for a proposed C^4I facility can be rather coarse, only to the depth necessary for estimating budgetary costs (see 21.3.2.2). The information will be refined and stated at an increased level of detail after project approval, when preparing the HEMP section of the facility requirements document (see 21.3.2.3).

The first steps in the process are to determine transattack and postattack missions and to develop a list of mission-essential equipment and systems needed for the performance of those missions. The mission data are used to evaluate applicability of MIL-STD-188-125. If the function is designated by the Joint Chiefs of Staff to be critical and time-urgent or when specified by a Military Department Headquarters or the Commander of a major command, requirements of MIL-STD-188-125 are mandatory. In these cases, both the hardening and verification test approaches are fixed by MIL-STD-188-125.

When the mission does not dictate compliance with MIL-STD-188-125, protection and testing methods can be prescribed by the requiring command. However, use of the standard to design and test HEMP protection subsystems of other ground-based C-E facilities with HEMP hardness requirements is encouraged to the extent permitted by budget constraints.

The MEE list provides the information to quantitatively scope the hardening program. It should include not only communications, data processing, and other technical systems, but also auxiliary equipment such as power generation and distribution, electronics cooling, and life support. For power generation, for example, the approximate load and mission/scenario timeline for operations without outside assistance (portable generators, fuel trucks, etc.) must be established. Needs for hardened site generators, UPS, fuel storage, and other related items can then be inferred. Based upon the identification of MEE, a rough estimate of the size of the protected volume is then made.

The third element—in addition to the hardening and verification approaches—that must be defined is the maintenance concept. The program recommended in handbook

section 20, consisting of organizational-level preventive and corrective maintenance and periodic hardness surveillance/reverification tests by an outside agency or contractor, will be assumed to be implemented.

The above level of definition, although elementary, provides sufficient information for the intended purpose. Cost estimating algorithms for MIL-STD-188-125 facilities will be supplied in the next subsection.

21.3.2.2 HEMP budget estimates. The acquisition of a new facility is contingent upon Congressional authorization of the MCP project, availability of resources to procure and install the equipment, and approval of funds to operate the system after it has been fielded. The HEMP program manager's second task, after initial establishment of hardening requirements, will be to prepare the budgetary cost estimates for the hardening portion of the system. Costs for the construction will be submitted on DD Form 1391, "FY 19 Military Construction Project Data," and the remaining costs will appear in other budget line items.

At the time of publication of this handbook, no facilities designed and built to the exact requirements of MIL-STD-188-125 have been completed. Several projects with similar specifications have been constructed, however, and experience-based cost data for these sites are summarized in appendix B. Estimating algorithms derived from these data are presented here. Figures are escalated as necessary to 1990 dollars. For fiscal years other than 1990, the amounts should be converted to construction-year dollars based upon standard DoD indices for military construction.

The estimating algorithms that follow are straightforward extrapolations of costs incurred on previous HEMP hardening and testing projects. It is likely that improved designs, construction methods, and test techniques can be developed, and that substantial savings could be realized by a concerted effort to reduce costs. A dialogue for exchanging cost savings ideas and accomplishments should be maintained between the design/ construction agencies and the centers of HEMP expertise.

HEMP protection subsystem construction costs include labor and materials for shield assembly, purchase or fabrication and installation of POE protective devices, and special protective measures provided under the building construction contract. They also include hardness quality assurance and acceptance testing, but not verification testing. These costs can be correlated to the total floor area within the protected volume and to the total surface area of the electromagnetic barrier. When the entire building is shielded, hardening costs can also be expressed as a fraction of the total construction contract price. Three formulas, applicable to facilities with floor areas from 280 m^2 (3000 ft^2) to 2800 m^2 (30,000 ft^2), areas follows:

$$C_c = \text{HEMP construction cost}$$
$$= \$1375 \times \text{floor area } (m^2)$$
$$= \$\ 128 \times \text{floor area } (ft^2) \qquad (27)$$

$$C_c = \$560 \times \text{barrier surface area } (m^2)$$
$$= \$\ 52 \times \text{barrier surface area } (ft^2) \qquad (28)$$

$$C_c = 0.38 \times \text{construction contract price} \qquad (29)$$

The resulting cost should be included in the DD Form 1391 as an item titled 'HEMP Protection." Progressively more accurate estimates will be prepared for the early preliminary, preliminary, and final design reviews. These should be "bottom-up" estimates based upon the hardening design features including floor or shield surface area, number and type of shielded doors, number and types of filter/ESA assemblies, etc.

HEMP hardening costs during the C-E equipment installation phase are generally small, since only a few HCIs associated with rf communications are usually provided under this effort. Unless the HEMP program manager has other information indicating extraordinary expenses, the recommended budgetary estimate is five percent of the HEMP construction cost:

$$C_I = \text{HEMP equipment installation cost}$$

$$= 0.05 \times C_c \qquad (30)$$

This figure does not include costs for any hardening provided at the equipment level during the hardware development program.

Virtually all MIL-STD-188-125-like hardness verification tests performed to date have been done by contractors, using Government-furnished simulation sources and instrumentation. Approximate contract price for test planning, conduct, and reporting as a function of the size of the facility is given by the graph in figure 188. If the contractor will be required to provide the test equipment, amortization costs for this hardware will increase the price by 2&35 percent. No figures for verification testing by a Government agency are presently available.

The estimate in figure 188 for verification testing assumes an average number of protected electrical POES. Since PCI testing constitutes roughly 40-50 percent of verification

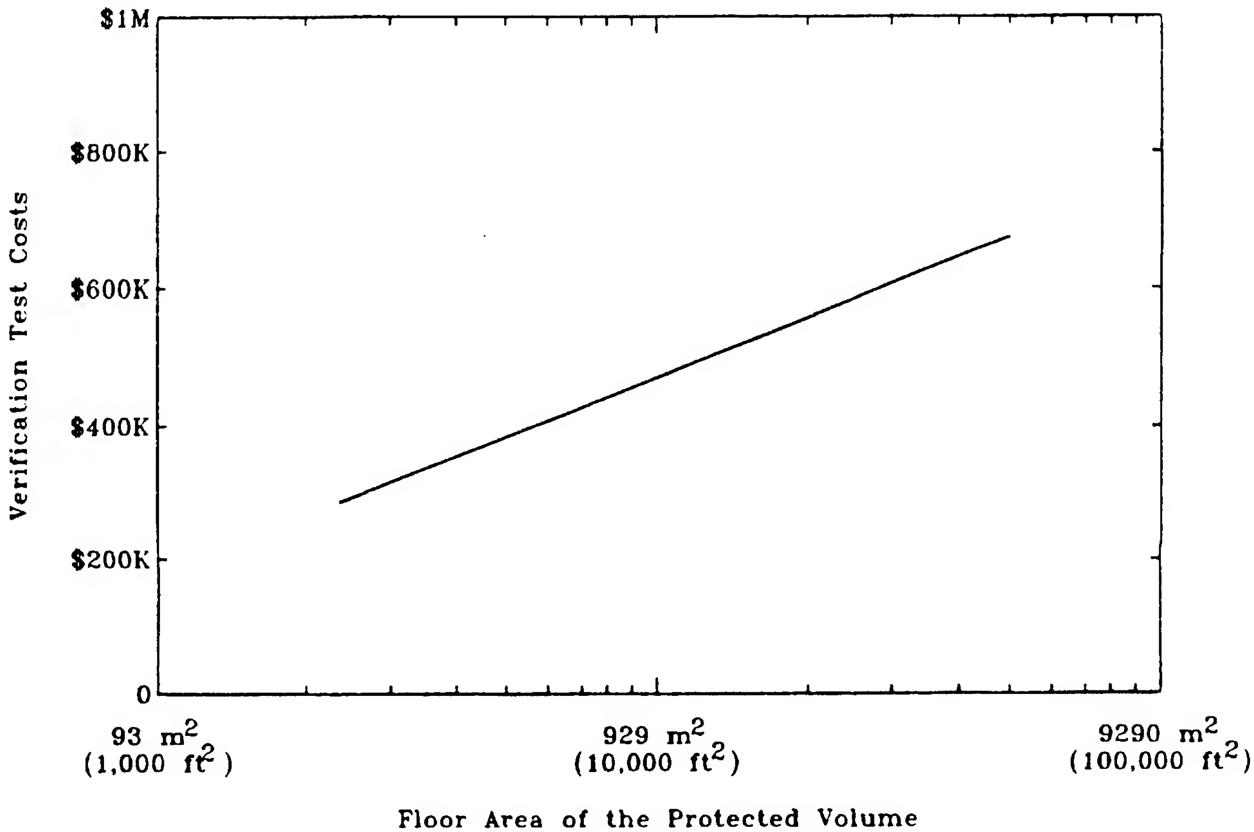


FIGURE 188. Estimate for verification test costs.

test costs in figure 188, significant savings can be realized by minimizing the number of electrical penetrations.

The database from which HM/HS costs can be estimated is extremely limited, because the organizational and procedural concepts for accomplishing these tasks are just now being formulated by the military services. Until better information becomes available, the following algorithm should be used:

$$C_{HM/HS} = \text{HM/HS cost}$$

$$= 0.07 \times C_c/\text{year} \tag{31}$$

The algorithm will be modified in a future handbook revision if experience indicates that a change is needed. It is estimated that approximately one-third of HM/HS costs will be for HCI preventive maintenance, inspections, tests, repairs, and replacements, and the remaining two-thirds will fund periodic hardness surveillance/reverification testing. An additional cost of approximately 5–10 percent of the HEMP construction cost will be required to develop the HM/HS program.

21.3.2.3 Facility HEMP requirements section. The facility requirements document is formally transmitted from the requiring and host commands to the design agent. Data item descriptions DI-E-1136, DI-S-3557, and DI-FACR-81045 should be reviewed to determine the type of information that must be provided. The document explicitly identifies functional requirements that the design and construction projects must satisfy for the delivered product to fulfill its intended purposes. HEMP hardening and other survivability requirements, when applicable, are included in the document.

Information to be provided in the HEMP section is basically a refinement of the hardness data developed to support the budget estimates. Again, the first step is to identify missions and MEE to be protected. To the extent practical, 'survivability"—allowable and unallowable system functional responses to a HEMP event-should be defined. Allowable disruptions are generally stated in terms of the type of disruption (bit errors in a data stream, loss of synchronization, etc.) and the maximum tolerable duration or recovery time from the outage. The system security guide should be consulted regarding the classification of such information, and classified data should be provided to the design agent only when essential to performance of the agent's duties.

The second step is to specify applicability of MIL-STD-188-125. For the remainder of the discussion, it will be assumed that MIL-STD-188-125 requirements are mandatory.

In almost all cases, the basic facility requirements document will contain a preliminary floor plan and site plan. The MEE that must be placed inside the electromagnetic barrier can be indicated by outlining the protected volume on the floor plan diagram. Similarly, special protection requirements for MEE outside the shield can be annotated on the site plan.

Definition of postattack support system requirements, based upon mission and scenario time profiles, can be very sit-specific and can be a significant task. This is illustrated with two examples:

a. If the postattack mission requires 200 kW of power and will be completed in one hour, hardened power requirements can be met with a UPS (rather than protected

generators). Furthermore, it may not be necessary for the environmental control system to survive.

b. Environmental and support systems must be protected when the mission requires extended, continuous operation while isolated from outside assistance.

An outline of the content to be included in the HEMP section is presented in table XXV. It is emphasized that this document contains requirements, but leaves the design solutions to the architect-engineer. The statement of requirements should be explicit, unambiguous, and complete.

21.3.2.4 HEMP program plan. The HEMP program plan is a document intended to support effective and efficient accomplishment of HEMP hardening requirements by providing the following information:

a. What tasks need to be done

b. Who will perform each task

c. How each task will be done

d. What products or documentation are to be produced

e. When each task will be accomplished

The plan should be developed by or under the supervision of the HEMP program manager, and it should be completed as soon as possible after project design authorization.

Organization of the plan can be by phase, task, participating agency, or any other manner that ensures completeness. There are several data item descriptions, including DI-ENVR-80262 and DI-NUOR-80156A, that can be useful to the preparer. A document organization by phase and task is suggested in table XXVI.

It is recommended that each service develop a generic nuclear survivability program plan, including a dedicated section for MILSTD-188-125 HEMP-hardened facilities, to serve as a guide for future managers.

All tasks-technical, management, administrative, and other—required for the HEMP hardening program should be included in the plan. A brief description of the work to be performed should be provided.

TABLE XXV. Content of the HEMP section in the facilities requirement document.

OUTLINE OF THE HEMP SECTION
IN THE FACILITY REQUIREMENTS DOCUMENT

I. MISSION - Identify functional capabilities with transattack and postattack survivability requirements.

II. THREAT DEFINITION - Identify DoD-STD-2169 (effective) as the definition of the HEMP threat environment.

III. HARDENING REQUIREMENTS - State the requirement for compliance with MI L-STD-188-125 (effective). (If MIL-STD-188-125 does not apply, provide a summary of the hardening approach.)

IV. EQUIPMENT TO BE PROTECTED - Identify equipment to be located within the protected volume and MEE outside the electromagnetic barrier to be hardened with SPMs.

V. SPECIAL REQUIREMENTS - Examples of special requirements include the following:

A. If the design or construction contractor is to provide part or all of the HM/HS plan, identify the products to be supplied.

B. Identify provisioning requirements when spares, repair parts, or special equip ment are to be provided under the construction contract.

C. If the entire backup power generation or electronics cooling system is not required to be protected, specify the required capacity of the hardened fraction.

D. If postattack environmental control requirements are different from those of the preattack condition, specify the postattack ranges.

TABLE XXVI. HEMP program plan outline.

I. INTRODUCTION - Identify the facility to be HEMP hardened, state the objectives and intended use, and provide an overview.

II. PLANNING, PROGRAMMING, AND BUDGETING PHASE

A. Task 1

1. Description
2. Responsibilities
3. Requirements and guidance
4. End products and documents
5. Milestones
6. Budget requirements by fiscal year

B. Task 2

:

III. DESIGN AND SPECIFICATION DEVELOPMENT PHASE

IV. CONSTRUCTION AND ACCEPTANCE TESTING PHASE

V. C-E EQUIPMENT INSTALLATION AND ACCEPTANCE TESTING PHASE

VI. HEMP VERIFICATION TESTING PHASE

VII. OPERATIONS AND SUPPORT PHASE

VIII. MANAGEMENT AND INTEGRATION - Show interactions between organizations, information flow, and an integrated schedule.

IX. BUDGET SUMMARY - Provide an expected budget by fiscal year for all HEMP-related activities and acquisitions.

X. SECURITY - Provide security guidance for design and test information that reflects the HEMP survivability status.

One of the most important objectives is to assign specific responsibilities to specific organizations, and this information should be provided in great detail. The preparer of the plan should address all of the following questions:

a. If a memorandum of agreement, statement of work, or contract is required, who is responsible for preparing this document?

b. Who is responsible for performing the work? If more than one organization does the work, who is responsible for which part?

c. Who is responsible for providing specifically identified data? Equipment? Other items?

d. Who reviews the progress and products?

e. Who approves or accepts the results?

The answers are recorded in "Responsibilities" paragraphs of the program plan.

References that establish requirements for the task or provide guidance in performing the work are identified in the plan. They may include directives and regulations, standards and specifications, guidelines and practices documents, and technical literature. When possible, specific articles of the references should be cited.

The "End products and documents" paragraphs identify expected outputs of each task.

The task schedules should indicate starting dates, intermediate milestones such as review meetings and draft submittals, delivery due dates, and projected approval/acceptance dates.

A schedule for the entire HEMP program, showing the integration of the individual tasks into a coherent whole, should be presented in the management section. Critical paths should be noted and should be carefully monitored by the HEMP program manager. Similarly, the budget summary section assists the HEMP program manager in tracking the project costs and in performing reallocations when necessary. The last section provides the guidance to ensure that classified information is properly safeguarded.

The HEMP program plan is primarily a management aid for the HEMP program manager. As such, it needs to be both thorough and realistic. Furthermore, it should be periodically reviewed and updated to reflect current information. The management section should also address the HEMP program manager's need for outside support. If required,

expertise and support can be obtained from the service center for HEMP technology or through contracting.

21.4 Design and specification development phase.

21.4.1 Milestones. The design and specification development phase of a HEMP-hardened facility acquisition is defined here to begin with the designation of the design agent and selection of the design architect-engineer. As shown in the milestone diagram of figure 189, the mainstream of activities includes the preparation of the design drawings and construction specifications. Planning for future phases-equipment installation, hardness verification, and O&S—which follow construction must also commence at this time, if schedule delays are to be avoided.

The design phase ends with approval of the drawings and specifications and authorization to proceed with construction. The final design submittals are combined with formal contract terms and provisions to create the invitation for construction bids package.

21.4.2 Execution. Development of a HEMP protection subsystem design and associated specifications to satisfy the requirements established by the facility requirements document is the responsibility of the design agent and the design contractor, not the HEMP program manager. The HEMP program manager meets the obligation to ensure that the design satisfies the requirements with thorough reviews and comments supplied to the design agent. It is the review element of design activities which will be emphasized here.

In addition to this mainstream effort, the HEMP program manager must ensure that prerequisites for later phases are initiated and proceeding at an appropriate pace.

21.4.2.1 Design contractor qualifications. Unless the facility design is to be done ‘in-house” by the Corps of Engineers or Naval Facility Engineering Command, the design agent will advertise the project in the Commerce Business Daily. An architectural and engineering firm will be selected from those who respond to develop drawings and specifications.

It is strongly encouraged that a contractor with successful past experience in HEMP design or one having a qualified consultant be chosen. The Commerce Business Daily announcement should include the following information:

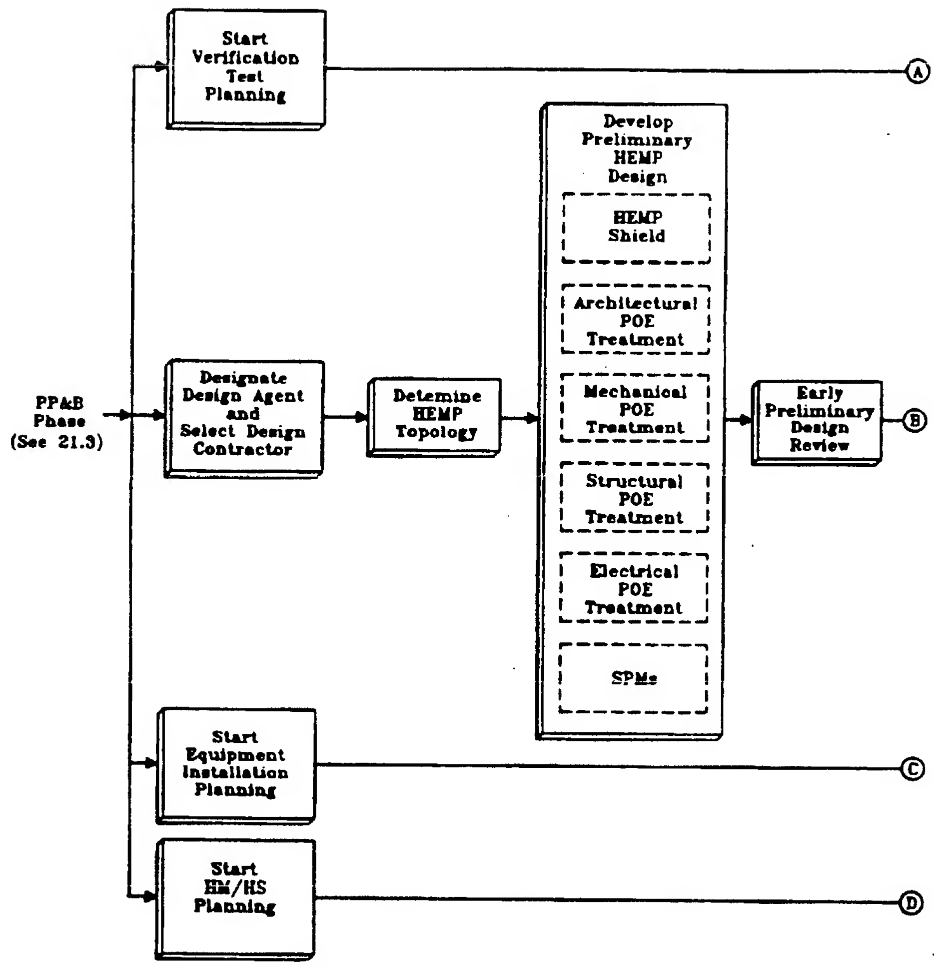


FIGURE 189. Design phase HEMP activites (continued on page 614).

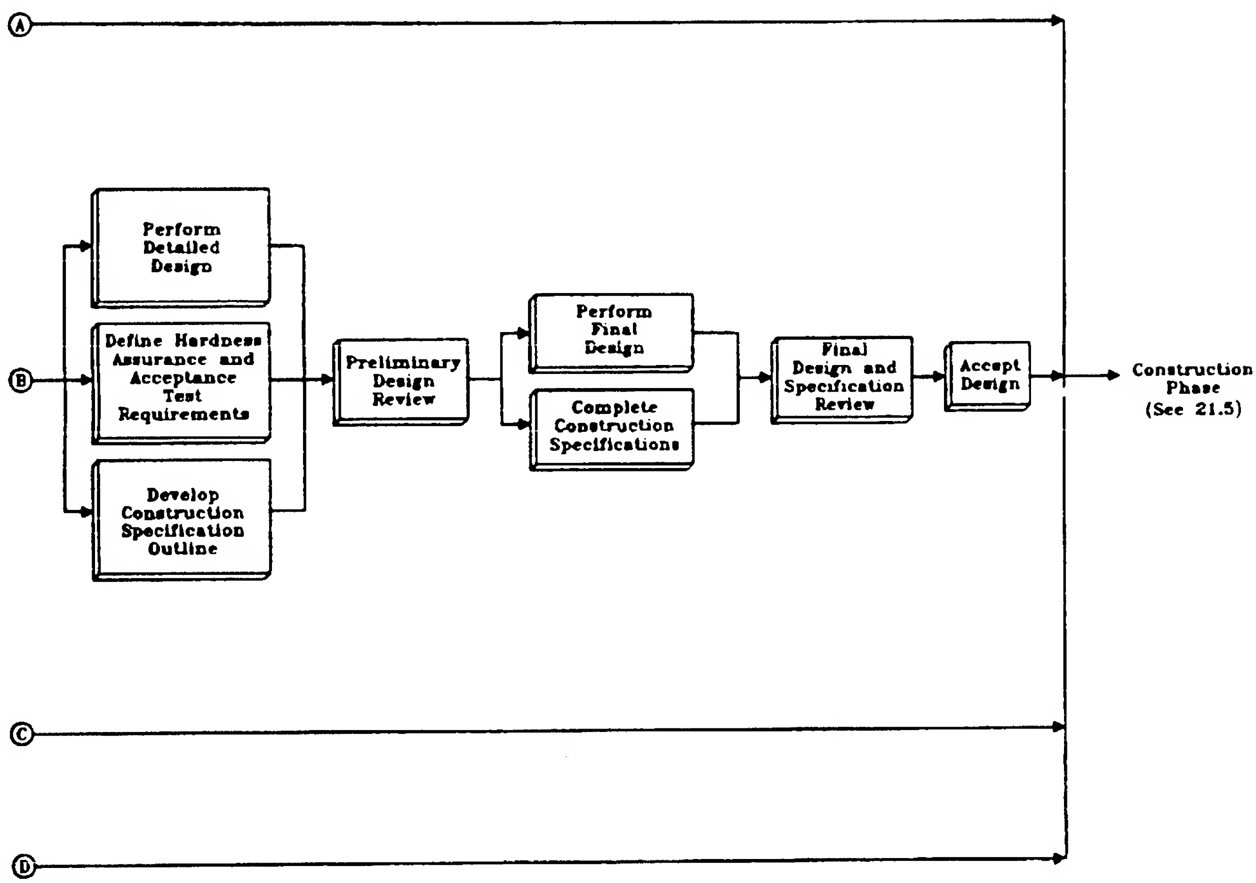


FIGURE 189. Design phase HEMP activities (continued from page 613).

a. "HEMP hardening design" explicitly identified in the description of work required

b. "Specialized experience in HEMP design" listed under the architect-engineer selection criteria

Information on previous HEMP experience and identification of the projects offered to meet the specialized experience criteria should be required in the submittal and reviewed during the interview. Contracting officers for the listed projects should be contacted to verify that performance was, in fact, satisfactory. If possible, a predesign conference should be held to ensure that the contractor understands the HEMP requirements before actual design is started.

21.4.2.2 HEMP design reviews. The design agent will schedule reviews at various stages of completion of the facility design. For a project that requires compliance with MIL-STD-188-125, at least three reviews-early preliminary (about 35 percent), preliminary (about 60 percent), and final (about 95 percent)–are strongly recommended.

Information to be provided at the early preliminary review is intended to reflect the designer's interpretation of the facility criteria. Drawings should include a preliminary site plan, floor plan and elevations, and concepts for architectural, mechanical, structural, and electrical systems. Barrier topology, including types and locations for personnel entryways and location of the penetration entry area, and major utility POEs should be identified. However, few detailed drawings will be available. Usually, a preliminary cost estimate will also be provided.

The HEMP program manager, supported as necessary with additional HEMP expertise, should review these drawings for correctness. However, it would be premature to comment on completeness. The following items should be checked:

a. The location of the electromagnetic barrier should be distinctively indicated on the floor plan and elevation drawings.

b. The barrier topology should enclose all MEE, except those that cannot be within the shield for functional reasons.

c. All entryways should be waveguide-below-cutoff or vestibule designs, with two shielded doors.

d. The PEA should be properly located with respect to entryways, and all utilities should penetrate in this area.

e. Annotations of HCIs and HCPs in accordance with MIL-STD-100 (reference 21–9) should appear on the drawings.

f. The design must accommodate hardness assurance during construction, acceptance testing, verification, and hardness maintenance and surveillance.

g. The cost estimate should reflect an understanding of the scope of shielding, POE protection, and HEMP quality assurance requirements; the basis of the cost estimate should be described.

Significant refinements to the design will occur between the early preliminary and preliminary reviews. The drawing package should now include typical wall, floor, and ceiling sections and selected details for shield fabrication. A penetration schedule and filter/ESA schedule should be provided, and the list of POEs should be virtually complete. Some (but not all) of the details for shielded doors, equipment access covers, piping and ventilation POE protection, and filter/ESA assemblies should be illustrated. Filters and ESAs should also be shown on electrical single-line diagrams, and door interlock and alarm circuits should be identified. The design analysis at this stage should address compliance with MIL-STD-188-125 PCI acceptance test requirements. An updated cost estimate should be provided; at this stage, the cost estimate should be based upon the number and type of doors, number and types of filter/ESA assemblies, actual requirements for special protection, and other site-specific design features.

Table XXVII provides a drawing review checklist for the HEMP program manager. It is meant to apply to both preliminary and final design reviews. While the overall topology of the HEMP protection subsystem and the POE list should be defined before the preliminary review, many of the detailed construction and installation drawings are not expected to be complete at this stage. The reviewers can assist the architect-engineer by identifying additional drawings to be supplied in the final package.

The HEMP program manager's review should concentrate on compliance with MIL-STD-188-125 requirements including reliability, maintainability, testability, safety and human engineering, and corrosion control.

At the final design review, the drawings should be final and must contain complete details, allowing the construction contractor to bid and build an acceptable HEMP protection subsystem.

21.4.2.3 HEMP specifications review. Preparation of the specifications for the construction project will normally be started some time after the early preliminary review. A coarse outline-sometimes consisting only of section numbers and names and the list

TABLE XXVII. Design checklist for preliminary and final reviews.

DESIGN REVIEW CHECKLIST

I. BARRIER TOPOLOGY

A. Barrier location clearly identified on drawings

B. Barrier is closed

C. All possible MEE is within the protected ,volume

D. The PEA is properly located and all possible POEs are located in this area

II. GROUNDING

A. Ground conductors do not penetrate the barrier

B. At least one connection to the earth electrode system at the PEA

III. SHIELDING

A. Steel or copper

B. All seams continuously welded or brazed

C. Details provided for all types of seams and joints

D. Built-in shield monitoring system

IV. POEs

A. Penetrations are minimized

B. All POEs are listed in the penetration schedule and details are provided

C. Entryways are waveguide-below-cutoff or vestibule designs, with interlocked and alarmed shielded doors

D. Equipment accesses are good rf designs

E. Piping and ventilation POE protection devices satisfy dimensional and construction requirements

F. Continuously welded or brazed seams and joints at structural POEs

G. Filter/ESA assemblies satisfy configuration and PCI performance requirements

H. HEMP protection conduits are rigid metal, circumferentially welded at all couplings

V. SPECIAL PROTECTIVE MEASURES

A. Detailed in sufficient depth for construction

B. Satisfy MIL-STD-188-125 requirements

VI. RELIABILITY AND MAINTAINABILITY - Properly considered

VII. TESTABILITY - Accommodates QA, acceptance. and verification test requirements

VIII. SAFETY AND HUMAN ENGINEERING - Properly considered and access for testing and maintenance is adequate

of guide specifications to be used—will usually be provided for the preliminary meeting, and a complete draft of the specifications will be supplied in advance of the final review. Unless a request for earlier information is made to the design agent and approved, there will be little specification material of substance to critique until the last review.

The HEMP program manager should request a summary of planned construction phase hardness quality assurance program requirements to be supplied at the preliminary review. Discussions of the requirements and resolution of any differences at this stage can avoid the need for major revisions at the final design review.

When the specifications are reviewed at the preliminary and final design reviews by the HEMP program manager, compliance with MIL-STD-188-125 is again the key criteria. The protection standard and the sample specification in appendix A of this handbook should be reread in preparation for this task. Careful attention should be given to each of the following items:

a. MIL-STD-188-125 should be cited as the mandatory standard; MIL-HDBK-423 should be referenced for guidance.

b. HEMP experience requirements for the construction prime contractor, HEMP protection subsystem subcontractor, and testing organization should be stated; data required to support the bidders' claims of successful past performance should be defined.

c. Changes to the HEMP protection subsystem design, including changes in shield materials or fabrication methods or additional penetrations, should be prohibited unless an adequate HEMP review has been performed and Contracting Officer approval is obtained.

d. Contractor submittals including qualification data, QC plans, shop drawings, HCI descriptive information, test plans and reports, operations and maintenance manuals, as-built drawings, and other deliverables should be explicitly specified. All information needed from the construction contractor to support development of the HM/HS plan should be identified as a required submittal. The Contracting Officer's authority to reject inadequate submissions should be noted.

e. Shielding effectiveness and electrical POE protective device transient suppression/attenuation requirements must be at least as stringent as those of MIL-STD-188-125.

f. Welding, welder qualification, and in-progress weld inspection requirements must be provided in detail.

g. Hardness assurance and acceptance test requirements and methods should be explicit and detailed; they must include at least the following elements:

- Ž In-progress inspection of welded and brazed shield seams and joints
- Ž A shielding effectiveness survey immediately after the shield is closed
- Ž Appropriate "in-factory" tests of shielded doors and filter/ESA assemblies
- Ž QA tests of special protective measures, as required
- Ž MIL-STD-188-125 acceptance tests

h. The Government should reserve the right to perform additional tests to verify compliance with the specifications, and to consider the test results in the acceptance decision.

i. All performance specifications, construction requirements, hardness assurance provisions, and special requirements (spares, maintenance procedures, etc.) must be explicit and detailed.

Prospective construction contractors, in order to be competitive, must bid and provide only the construction and construction-related tasks defined by the drawings and specifications. Everything needed by the Government to achieve the operationally required survivability must therefore appear in the HEMP protection subsystem section of the MCP documents. By thorough design phase reviews, the HEMP program manager can avoid the need for costly change orders during facility construction.

21.4.2.4 Preparations for future phases. Planning activities to support the future equipment installation phase, the hardness verification test program, and facility O&S requirements should commence as soon as practical after project approval. A schedule should be established for each of these efforts. It should be correlated to design and construction milestones and should be continuously updated so that prerequisites are accomplished by the appropriate time.

The first elements in preparing for the C-E equipment installation are to generate the agreement (or agreements) under which the installing command will operate and to develop the solicitation package, if contractor support is required. The HEMP program manager provides inputs to these documents at an information level comparable to data in the HEMP section of the facility requirements. Once the agreement and contract have been negotiated and signed, the equipment installation plan is started. Participation in design reviews and site visits during construction by personnel from the installing command is beneficial for ensuring exchange of information and proper building-equipment interfaces. HEMP aspects of the installation plan are addressed in 21.6.2.1.

An interagency understanding and a contracting action may also be needed for the verification test phase. Responsibility for drafting the technical portions of these formal agreements will generally be assigned to the HEMP program manager. The work will include test plan development, collection and checkout of test equipment, performance of the measurements, and documentation of results (see 21.7.2). Once again, it is highly desirable for the verification testing organization to be represented in the design review and construction surveillance processes.

The HM/HS plan, the contents of which will be discussed in 21.8.2.1, implements the maintenance concept with detailed and site-specific configuration data and procedures. It must be prepared in advance, so that preservation techniques are available when HCISs are accepted from the builder or installer. It is likely that the HEMP program manager will write the statement of work for this effort and act as the technical point of contact in securing services of the organization or contractor that will prepare the HM/HS plan.

The agreements, contracts, and statements of work for tasks described above should be carefully drafted. They should define obligations of the parties, nature of the work to be performed, and the products to be delivered. And they should be prepared and executed promptly.

21.5 Construction and acceptance testing phase.

21.5.1 Milestones. The construction phase is considered to cover the period from designation of the construction agent through building acceptance by execution of the DD Form 1354, 'Transfer and Acceptance of Military Real Property." Significant HEMP activities during this phase are identified in figure 190.

Construction of the building, including associated site work and all or nearly all of the HEMP protection subsystem, constitutes the principal effort occurring during the construction phase. The products to be delivered must comply with the design drawings and specifications, unless deviations are approved. The construction contractor also prepares submittals and performs testing, when these items are explicitly required by the bid package.

Other activities taking place in parallel with the construction effort include the following:

a. Government surveillance of construction – including review of submittals, inspection of work, witnessing contractor tests, and performing any independent Government tests.

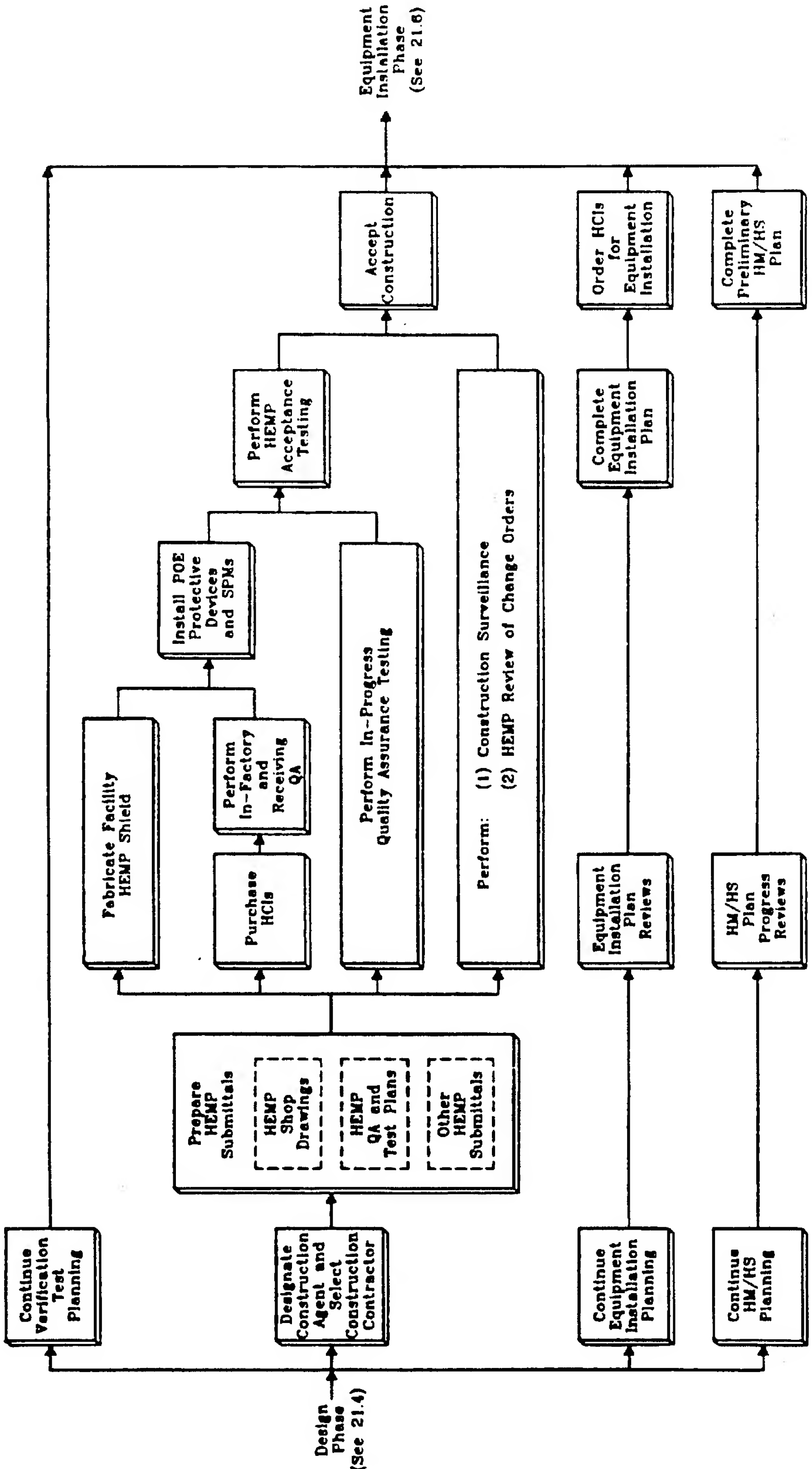


FIGURE 190. Construction phase HEMP activities.

b. Preparations for equipment installation – the equipment installation plan, including HEMP hardening elements, must be completed and approved; equipment, components, material, and other items needed to start work after building acceptance must be acquired.

c. Preparations for verification testing continue.

d. HM/HS plan development - a preliminary version covering HCIs provided under the construction contract must be completed, so that maintenance can be accomplished during the equipment installation phase.

21.5.2 Execution. There are many similarities between the HEMP program manager's duties during the construction phase and those previously described for the design phase. The manager is not directly responsible for the HEMP construction, construction hardness assurance, or acceptance testing, but should perform surveillance of these activities. Similarly, the HEMP program manager must monitor the progress of HEMP aspects of the preparations for C-E equipment installation and must ensure that developments of the verification test plan and HM/HS plan are proceeding satisfactorily.

21.5.2.1 Construction contractor qualifications. It is also strongly recommended that past experience in comparable HEMP hardening projects be a significant factor in choosing the construction contractor. To obtain the information for evaluating a candidate's qualification, the following actions should be taken:

a. "HEMP hardening" should be explicitly identified in the Commerce Business Daily announcement description of work to be performed.

b. "Specialized experience in HEMP construction" should be listed in the Commerce Business Daily announcement as a criterion for contractor selection.

c. Interviews should be conducted and should include discussions of the prime contractor's and the principal HEMP protection subcontractor's qualifications and experience on comparable HEMP hardening projects, including HEMP personnel resumes and specific information on previous jobs.

Claims of satisfactory performance on previous jobs should be verified.

21.5.2.2 Review of construction contractor submittals. The construction specifications will require certain submittals, such as shop drawings and QC and test plans, from the contractor to the construction agent. Most submittals and all contractor-proposed

changes to the design must be approved by the Contracting Officer before implementation. The HEMP program manager should be on the distribution list for these submittals, should carefully review them, and provide timely comments and recommendations to the construction agent.

The HEMP reviews should address electromagnetic performance, reliability, maintainability, testability, and compliance with other requirements of MIL-STD-188-125. They should be performed promptly and completed in accordance with the construction agent's schedule, so that the Government does not become liable for project delays.

21.5.2.3 HEMP construction surveillance. Exclusive responsibility for supervising the construction contractor's work is assigned to the construction agent. When the project includes HEMP hardening, the construction agent's resident should be trained in HEMP construction techniques and have relevant prior experience if possible. If a resident with these credentials is not available, ready access to qualified HEMP assistance should be provided. Such support can be obtained from the service centers of HEMP expertise, from the Defense Nuclear Agency, or by contract.

The HEMP program manager' is strongly encouraged to periodically go to the construction site and observe the progress of the HEMP protection subsystem fabrication and assembly. There are two reasons for this suggestion:

a. To verify that the HEMP protection subsystem, as-installed, will provide the operationally required hardness.

b. To obtain site configuration data that will enhance effectiveness in monitoring the developments of the equipment installation plan, the verification test plan, and the HM/HS plan.

These objectives are equally important.

Visits should be coordinated through the construction agent. The HEMP program manager should be on the distribution list for formal notifications from the contractor, in order to coordinate scheduled trips with the occurrence of test events. A construction surveillance checklist is provided in table XXVIII.

Comments and recommendations should be provided in written correspondence to the construction agent. The HEMP program manager should not attempt to give direction to the resident inspector or the contractor.

TABLE XXVIII. Construction surveillance checklist.

CONSTRUCTION SURVEILLANCE CHECKLIST
FOR HEMP PROGRAM MANAGERS

I. Inspect installed HCIs

   A. Verify compliance with MIL-STD-188-125, design drawings and specifications, and contractor submittals

   B. Observe quality of work

II. Observe operation of the contractor's quality assurance program

   A. Verify compliance with MIL-STD-188-125, specifications. and the contractor-prepared plan

   B. Review recent quality control reports

III. Observe tests in progress

   A. Verify compliance with MIL-STD-188-125, specifications, and test plans

   B. Review results of recent tests

IV. Inspect HCIs in storage for condition and adequacy of environmental protection

V. Record information useful for the performance and review of parallel tasks

VI. Discuss project status with the construction agent's resident inspector

   A. Progress and problems

   B. Status of change orders

   C. Observations during the visit

VII. Provide comments and recommendations in writing to the construction agent

The HEMP program manager, with the concurrence of the construction agent, may also witness "in-factory" tests at suppliers' facilities.

21.5.2.4 HEMP review of proposed construction change orders. Formal reviews of drawings and specifications are scheduled at various stages of completion of the design process, and the HEMP program manager has these opportunities to assess and comment on the adequacy of the protection subsystem (see 21.4.2.2). Since seemingly insignificant changes can markedly affect the quality of hardening, HEMP review of all proposed change orders during the construction phase should also be instituted. This should include both modifications initiated by the Government and those recommended by the contractor.

A procedure by which the HEMP program manager reviews change order documents for hardening impacts prior to approval should be established. A formal configuration control board, with the HEMP program manager as a member, is the most effective means for ensuring that HEMP and other aspects of the change are properly evaluated. A change affects the HEMP protection under any of the following conditions:

a. When it adds a penetration of the electromagnetic barrier or modifies an existing POE protective treatment

b. When new MEE or nonessential equipment interconnected with MEE will be installed outside the barrier

c. When MEE location with respect to the electromagnetic barrier (inside vs. outside) is altered

d. When shield materials, assembly details, or fabrication techniques are modified

e. When intersite conductors are added to the site plan

f. When a configuration or equipment change is likely to require use of SPMs

If the change order includes any of these items, the HEMP program manager must ensure that the affected HCIs are properly engineered and will be implemented in accordance with applicable requirements of MIL-STD-188-125.

21.5.2.5 Acceptance testing. MIL-STD-188-125 requirements for HEMP protection subsystem acceptance are quite explicit. Testing must include the following sequences:

a. Shielding effectiveness testing of the primary electromagnetic barrier and special protective barriers in accordance with appendix A of the standard

b. PCI testing of electrical POE protective devices in the primary electromagnetic barrier and special protective barriers in accordance with appendix B of the standard

c. Other tests of SPMs as necessary to demonstrate compliance with the particular performance requirements

The standard also provides instructions for the test plan and test report and includes generic procedures. Handbook section 16 also discusses these requirements.

It is strongly recommended that the acceptance testing be performed by an independent testing organization hired by and reporting directly to the construction agent. The test plan, outlined in table XXIX, will be written by the responsible party and submitted for approval to the construction agent. The HEMP program manager should carefully review this document for compliance with MIL-STD-188-125 and specification requirements, and comments should be provided in writing to the construction agent.

The HEMP program manager should schedule a construction surveillance site visit (see 21.5.2.3) to coincide with performance of the acceptance test.

An outline for the acceptance test report appears in table XXX. There are only two possible conclusions: pass or fail. Any deficiencies found by acceptance testing should be corrected and retested before the DD Form 1354 is executed, or the deficiencies and the need for retesting should be noted on this form.

The HEMP acceptance test is extremely important, because it represents the final opportunity to demonstrate HEMP protection subsystem performance before the construction contractor receives payment and departs. Problems uncovered after this event will become the responsibility of the Government. The HEMP program manager should therefore ensure that the test plan is complete, that all performance demonstrations are performed in accordance with the procedures, and that the test report accurately reflects the measurements. It should also be ensured that the procedures and results are preserved, to be used as baseline data for the HM/HS program.

As a final comment, it should be noted that test plan and test report data item descriptions cited by MIL-STD-188-125 have been superseded by DI-NUOR-80928, "'Nuclear Survivability Test Plan," and DI-NUOR-80929, "Nuclear Survivability Test Report," respectively. Assistance in identifying effective data item descriptions that may be specified in DoD contracts is provided in handbook appendix C.

21.5.2.6 Preparation for future phases. Planning for C-E equipment installation, verification testing, and facility O&S continue through the construction phase. The

TABLE XXIX. Acceptance test plan outline.

HEMP ACCEPTANCE TEST PLAN OUTLINE

I. INTRODUCTION - Identify the facility to be tested and state the test objectives; provide an overview of the tests to be performed.

II. FACILITY DESCRIPTION - Provide a site plan, a floor plan of the protected volume, a list of shield POEs and the POE protective devices, and a list of special protective measures installed; provide a narrative description as required.

III. SHIELDING EFFECTIVENESS TEST PROCEDURES - Provide the following information:

- A. Plan and elevation drawings identifying plane wave and magnetic field test areas: identification of electric field test points, when required
- B. Specific test frequencies; identify frequency coordination requirements
- C. Test equipment identification by manufacturer, model, and serial number
- D. Detailed calibration and test procedures
- E. Procedures for marking, repair, and retest of defects
- F. Deviations from requirements of appendix A to MIL-STD-188-125

IV. PULSED CURRENT INJECTION TEST PROCEDURES - Provide the following information:

- A. Identification of POE protective devices to be tested by functions and manufacturers' part numbers: attach manufacturers' data sheets in an appendix
- B. Test points and injection levels
- C. Simulation and data acquisition equipment identification by manufacturer, model, and serial number
- D. Detailed calibration and test procedures
- E. Deviations from requirements of appendix B to MIL-STD-188-125

V. TESTS OF SPECIAL PROTECTIVE MEASURES - Provide descriptions of the SPMs to be tested, locations of test points, and identification of simulation and data acquisition equipment by manufacturer, model, and serial number: provide detailed calibration and test procedures.

TABLE XXIX. Acceptance test plan outline (continued).

VI. DATA MANAGEMENT - Provide the following information:

A. Data quality control procedures, including acceptability criteria

B. Data processing requirements and algorithms

C. Procedures for identifying and preserving data

D. Pass/fail criteria

VII. SAFETY PLAN - Identify test hazards and procedures for protection of personnel and equipment.

VIII. SECURITY PLAN – Identify clearance and access requirements for test personnel; outline procedures for protection of classified data

IX. TEST MANAGEMENT - Identify test participants, by agency or company, and responsibilities: identify all site support requirements: provide test schedule.

TABLE XXX. Acceptance test report.

HEMP ACCEPTANCE TEST REPORT OUTLINE

I. INTRODUCTION - Identify the facility tested and state the test objectives: reference the test plan.

II. DEVIATIONS FROM THE TEST PLAN - Identify all deviations from the test plan and provide rationale for these departures.

III. DATA - Provide copies of all measured and processed results; all data must be annotated to permit identification of the measurement location, test conditions, and conversion to engineering units.

IV. DATA SUMMARY - Provide a succinct data summary. in tabular form, which characterizes the measured results.

V. PASS/FAIL CONCLUSIONS

opportunity to examine actual hardware significantly enhances the ability to be detailed and specific on these tasks.

Several of the preparatory items must be completed by the time the building is accepted from the construction contractor and agent; they include:

a. The installation plan (see 21.6.2.1)

b. Ordering, receipt, and transport to the site of equipment, components, and materials required in the early stages of installation

c. A preliminary version of the HM/HS plan (see 21.8.2.1), covering HCIs delivered under the construction contract

The HEMP program manager should monitor the progress of these efforts and verify that the products will be available when needed, and should update the budget estimates as required.

21.6 C-E equipment installation and acceptance testing phase.

21.6.1 Milestones. Commercial/industrial equipment, such as power generation and distribution, HVAC, and plumbing hardware, will usually be provided under the construction contract. The remaining equipment—generally including communications, data processing, and other technical systems—will be supplied during the C-E equipment installation phase. Some additions and modifications to the HEMP protection subsystem may be required as part of this installation. Thus the mainstream HEMP milestones in this phase (figure 191) are similar to construction phase HEMP activities.

Upon completion of checkout of the equipment supplied under the C-E installation plan, responsibility for the entire facility is assumed by the O&S staff. Mission operations can commence at this time, and the hardness verification test program should be performed as soon thereafter as practical. The verification test plan and HM/HS plan must therefore be completed during C-E equipment installation.

21.6.2 Execution. The installing command is generally responsible for planning this phase, providing materials, performing the actual installation, and conducting the functional checks of the C-E equipment. When additions or modifications to the HEMP protection subsystem are involved, their memorandum of agreement or statement of work must include virtually all of the items-- -HEMP design, HEMP installation, QC, and acceptance-which were part of the building design and construction scope. The level

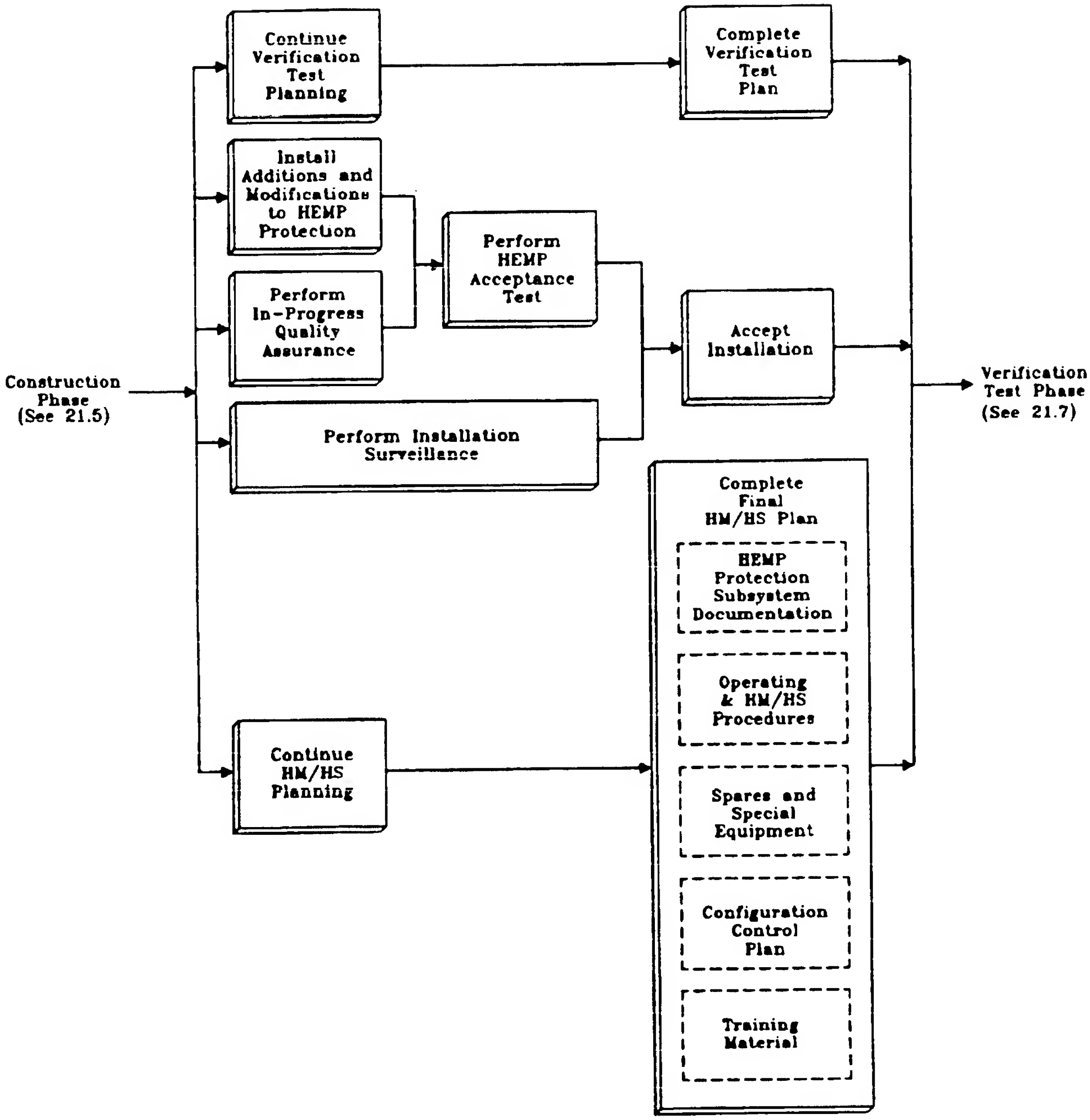


FIGURE 191. HEMP activities during C-E equipment installation phase.

of effort related to the HEMP program will generally be much smaller, however, since relatively few HCIs are anticipated to be supplied in this phase.

HCIs supplied under the building construction phase must be maintained during the installation period. Usually, some members of the O&S staff have reported by this time and will be responsible for these tasks.

21.6.2.1 Installation plan development. The C-E equipment installation plan is developed during the building design and construction phases by the installing command, and it should be completed, approved, and ready to implement when the DD Form 1354 is executed. For all practical purposes, installation planning is a parallel design phase for a different part of the system than that for which the architect-engineer is responsible.

The same MIL-STD-188-125 performance and test requirements that are levied on the building MCP also apply to HEMP tasks included with the equipment installation. Therefore, the HEMP program manager has the same obligation to ensure that the 'design" is in accordance with the standard and that the installation procedures contain the appropriate hardness assurance and acceptance provisions.

21.6.2.2 Installation surveillance. It is also recommended that the HEMP program manager periodically visit the facility during installation of the C-E equipment. Reasons for the visits and the activities to be observed are virtually identical to those described earlier for construction surveillance (see 21.5.2.3).

Tips should be scheduled with the officer-in-charge of the site during the installation, and comments and recommendations should be communicated in writing.

21.6.2.3 Installation acceptance testing. HCIs supplied as part of the C-E equipment installation are subject to the same acceptance requirements as those provided under the construction contract (see 21.5.2.5). The HEMP program manager should ensure that these requirements are reflected in the installation plan and included in phase performance. The HEMP program manager should be represented during performance of the acceptance test.

21.6.2.4 Preparations for future phases. Initial operating capability occurs immediately after completion and acceptance of the equipment installation, and mission performance begins. Since the verification test is conducted as soon after initial operating capability as possible, the test plan (see 21.7.2.1) must be finalized and approved during this fourth phase. The HEMP simulation sources and test data acquisition systems should

be collected, calibrated, and shipped to the site well before the scheduled start date of measurements.

Full implementation of the HM/HS plan (see 21.8.2.1) should also begin at this time. This implies that the plan must be completed during equipment installation and that required material and supplies must be on hand.

21.7 Verification testing phase.

21.7.1 Milestones. Although verification testing occurs in parallel with site O&S, it has been designated here as a separate phase to highlight significant HEMP activities which take place during the period. As shown in figure 192, these milestones are as follows:

a. Coordination between site personnel and the organization that will perform the hardness verification testing

b. Test performance

c. Publication of the verification test report

d. Initiation of corrective actions, if hardening deficiencies are discovered

21.7.2 Execution. The verification testing organization will prepare the test plan and report and will perform the measurement program. The HEMP program manager is responsible for reviewing these documents, witnessing part or all of the testing, and initiating corrective actions if deficiencies are found. Technical aspects of the verification program are discussed in section 16.

Transfer of HEMP responsibility from the HEMP acquisition program manager to the on-site HEMP program manager will occur sometime between the end of equipment installation and the end of the verification program. This should be coordinated so that the division of management functions for the test phase is unambiguous.

21.7.2.1 Verification test plan. The planning for the verification test should be started in parallel with the facility design effort, and it continues through the construction and equipment installation phases. The detailed test plan should be completed and approved before initial operating capability. Therefore, the acquisition HEMP program manager will have responsibility to oversee the planning activity.

Once again, MIL-STD-188-125 and DI-NUOR-80928 provide explicit direction on verification test program requirements and instructions for test plan preparation. An

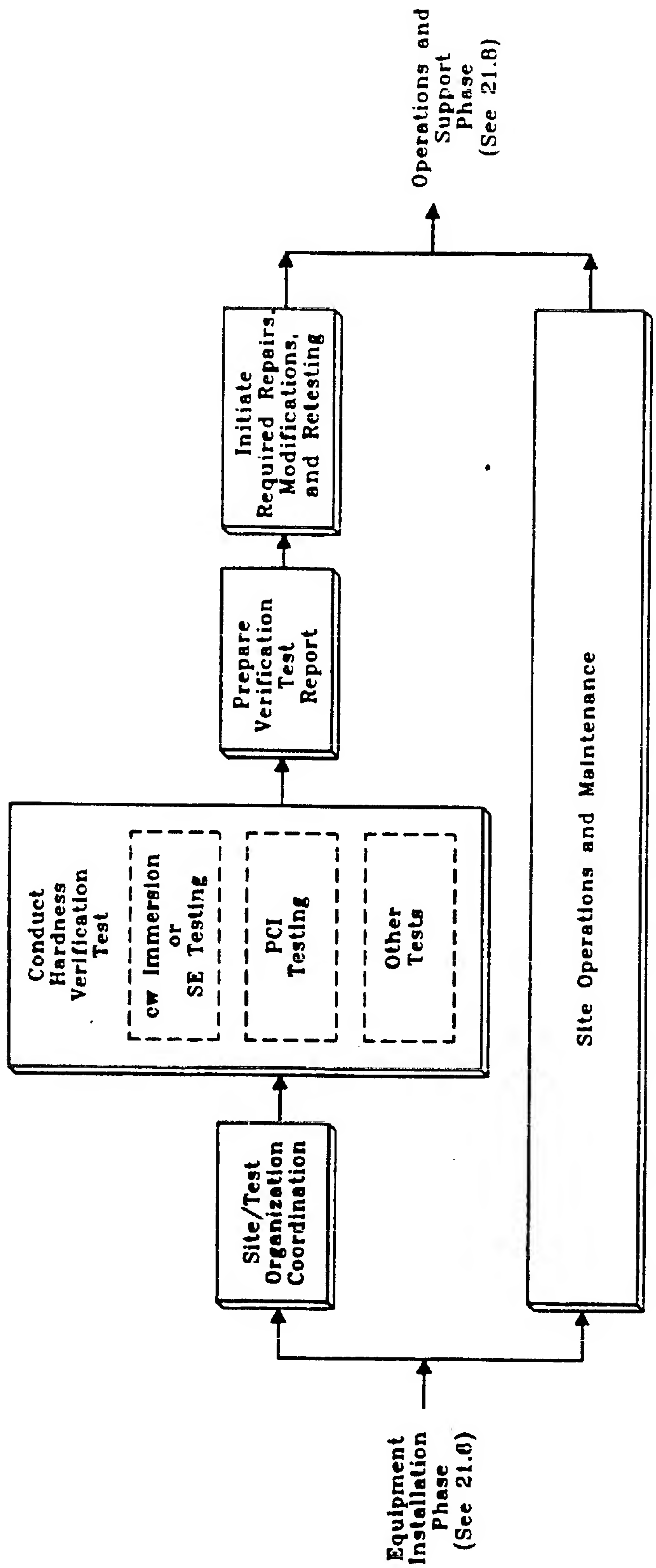


FIGURE 192. HEMP verification test activities.

outline for the document has been developed from the guidance contained in the standard, and it is presented in table XXXI. The test plan should include clear pass/fail criteria for functional testing and should identify special diagnostic equipment and software when required. The plan should also anticipate and schedule time for investigation of anomalies and malfunctions.

The HEMP program manager reviews the plan for completeness and compliance with MIL-STD-188-125 and provides comments to the preparer, normally the verification testing organization. The review requires an intimate knowledge of the facility HEMP protection subsystem, acquired through management participation in all aspects of the development process. After the plan is satisfactory and has been finalized, the appropriate approvals are obtained. Coordination efforts are then initiated and a start date for the measurement program is set.

21.7.2.2 Verification test execution. Performance of a complete MIL-STD-188-125 hardness verification test will require approximately four to eight weeks on site for a small or moderately sized installation. The test team generally consists of up to eight engineers and technicians. The tests may be performed sequentially, or one group may conduct the low-level cw immersion and shielding effectiveness measurements, while a second performs PCI tests of electrical POE protective devices.

The vast majority of measurements can be made while the facility is actively engaged in mission operations. The flexibility usually designed into these sites allows shifting of on-line equipment so that individual circuits can be deenergized for test purposes.

In a small number of instances, a critical circuit without a backup must be temporarily disabled. Typically, 8-16 hours of mission downtime will be necessary at some time during the test program.

One site staff member should be assigned on essentially a full-time basis to coordinate test events with normal facility activities. Additional support from operators in monitoring functional behavior of systems in response to simulated HEMP excitations will also be needed. Storage for classified data and portable instruments, work bench areas, and a meeting room for test team conferencing are other typical site support requirements.

It is a common practice to schedule a brief meeting at the start of each test day to review planned test activities with facility personnel. Requests for additional assistance including operators to monitor functional performance are addressed at that time.

TABLE XXXI. HEMP verification test plan outline.

HEMP VERIFICATION TEST PLAN OUTLINE

I. INTRODUCTION - Identify the facility to be tested and state the test objectives: provide an overview of the tests to be performed.

II. FACILITY DESCRIPTION - Provide a site plan, a floor plan of the protected volume, lists of MEE inside and outside the electromagnetic barrier, a complete list of shield POEs and POE protective devices, and a complete description of all special protective measures: provide narrative as required.

III. SHIELDING EFFECTIVENESS TEST PROCEDURES (when applicable) - Provide the following information:

   A. Plan and elevation drawings identifying plane wave and magnetic field test areas

   B. Specific test frequencies: identify frequency coordination requirements

   C. Test equipment identification by manufacturer, model, and serial number

   D. Detailed calibration and test procedures

   E. Procedures for marking, repair, and retest of defects

   F. Deviations from requirements of appendix A to MIL-STD-188-125

IV. PULSED CURRENT INJECTION TEST PROCEDURES - Provide the following information:

   A. Identification of POE protective devices to be tested by functions and manufacturers" part numbers: attach manufacturers' data sheets in an appendix

   B. Test points and injection levels

   C. Simulation and test acquisition equipment identification by manufacturer, model, and serial number

   D. Detailed calibration and test procedures, including facility and circuit configuration and equipment operating state requirements

   E. Provisions for functional monitoring

   F. Deviations from requirements of appendix B to MIL-STD-188-125

TABLE XXXI. HEMP verification test plan outline (continued).

V. CW IMMERSION TEST PROCEDURES (when applicable) - Provide the following information:

A. Transmitting antenna and reference sensor locations

B. Measurement points

C. Illumination system and data acquisition equipment identification by manufacturer, model, and serial number

D. Detailed calibration and test procedures, including facility configuration and equipment operating state requirements

E. Provisions for functional monitoring

F. Deviations from requirements of appendix C to MIL-STD-188-125

VI. TEST OF SPECIAL PROTECTIVE MEASURES - Provide descriptions of SPMs to be tested, locations of test points, and identification of simulation and data acquisition equipment by manufacturer, model, and serial number; provide detailed calibration and test procedures.

VII. OTHER TESTS - Provide comparable descriptions of other tests to be performed (although these tests may not be required by MIL-STD-188-125).

VIII. DATA MANAGEMENT - Provide the following information:

A. Data quality control procedures, including acceptability criteria

B. Data processing requirements and algorithms

C. Procedures for identifying and preserving data

D. Pass/fail criteria

IX. SAFETY PLAN - Identify test hazards and procedures for protection of personnel and equipment.

X. SECURITY PLAN - Identify clearance and access requirements for test personnel: outline procedures for protection of classified data.

XI. TEST MANAGEMENT - Identify test participants. by agency or company, and responsibilities: identify all site support requirements. provide test schedule and highlight mission downtime requirements.

The HEMP program manager is encouraged to participate as fully as practical in verification test conduct.

21.7.2.3 Verification test report. The test team will normally provide a preliminary briefing on test results before departing the facility. Program data and findings will then be formally published in the test report. MIL-STD-188-125 and DI-NUOR-80929 requirements for this document are summarized by the outline presented in table XXXII. If the data acquisition system is highly automated, compilation and analysis for the report can normally be completed in two to three months.

The primary purposes of the test report are to provide a permanent record of the testing and to identify deficiencies in the HEMP protection subsystem for repair or modification. After thoroughly reviewing the document, the HEMP program manager should take prompt and appropriate action to investigate and rectify the problems.

The secondary function of the report is to serve as baseline data on the recently completed facility for future comparisons to HS data. Copies of the report should be provialed to site maintenance personnel and to the agency designated to perform surveillance/reverification tests.

21.7.2.4 Correction of deficiencies. The return on the verification investment comes from the elimination of HEMP hardening deficiencies, that might lead to mission interruption at a time of crisis. Therefore, the HEMP program manager should take prompt corrective actions on problems found by the hardness verification program.

In many cases, only a simple repair or replacement will be necessary. The cause and effect relationship between application of the simulated HEMP excitation and an upset or failure is not always obvious, however, and an engineering study might be required for resolution. In either case, the needed steps should be initiated as soon as practical.

21.8 Operations and support phase.

21.8.1 Milestones. O&S for the HEMP protection subsystem, as illustrated in figure 193, is essentially the same as the O&S phase for any other equipment. Hardness critical items must be operated, maintained, and monitored in accordance with established procedures, and other actions must be taken as needed to maintain operational effectiveness. Personnel must be trained to perform these tasks. Configuration control must be exercised. All of these elements are integral to a total HM/HS plan.

TABLE XXXII. HEMP verification test report outline.

HEMP VERIFICATION TEST REPORT OUTLINE
I. INTRODUCTION - Identify the facility tested and state the test objectives: reference the test plan and provide a verification program overview.
II. DEVIATIONS FROM THE TEST PLAN - Identify all deviations from the test plan and provide supporting rationale.
III. DATA - Provide copies of all measured and processed results: all data must be annotated to permit identification of the measurement location, test conditions. and conversion to engineering units.
IV. DATA SUMMARIES - Provide a succinct data summary, in tabular form, which characterizes the measured results.
V. TEST CHRONOLOGY - Provide a chronology of events and identification of failures, upsets, or interference observed: describe conditions under which abnormal events occurred and results of subsequent investigations.
VI. CONCLUSIONS - Provide a definitive statement of HEMP hardness of mission functions based upon all test results and supporting analyses: identify any failure to meet shielding effectiveness, PCI, or cw immersion pass/fail criteria; discuss results of investigations of failures: provide options for corrective action and recommended solutions, if applicable.

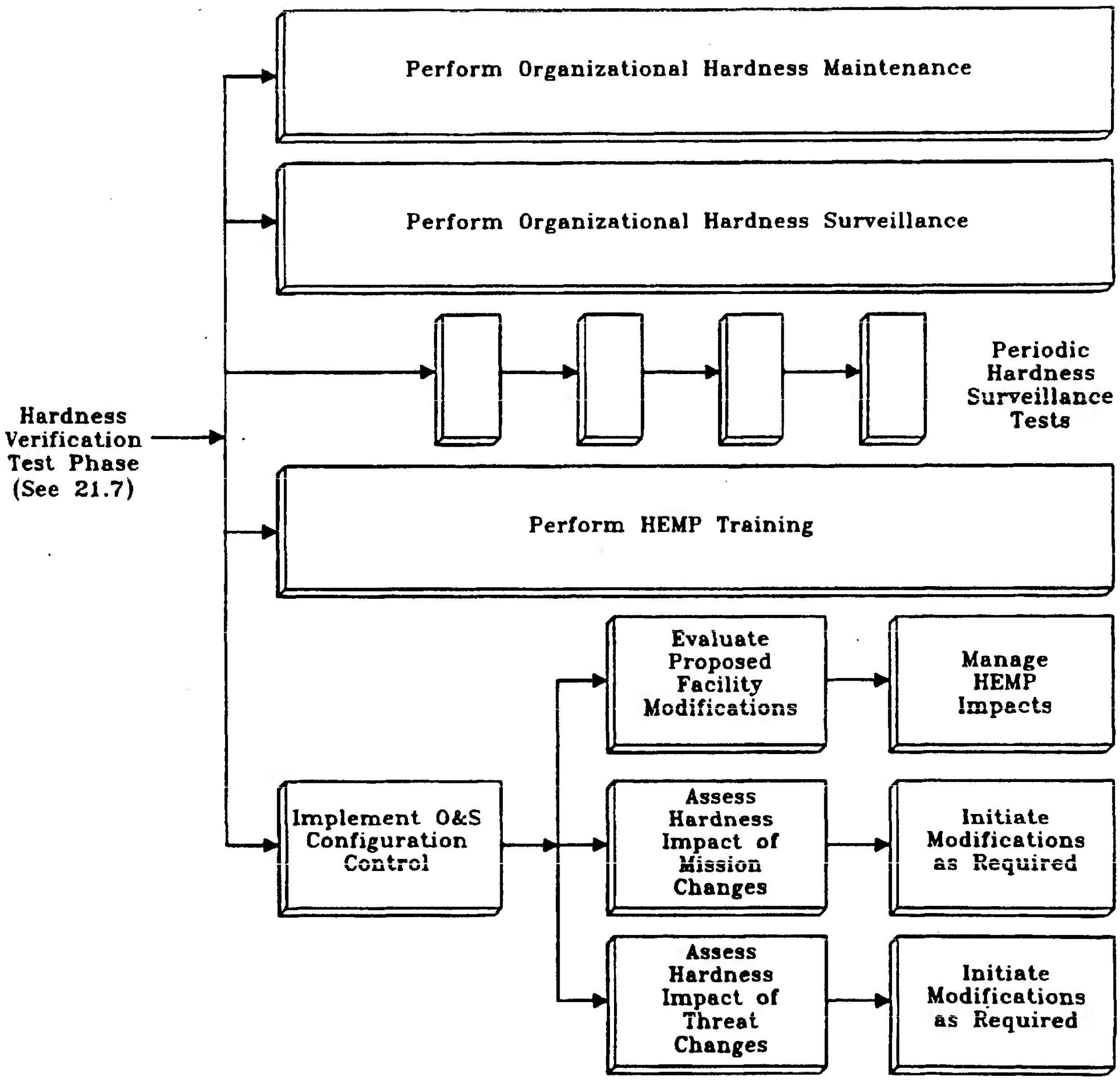


FIGURE 193. HEMP activities during O&S.

21.8.2 Execution. Responsibility for the HEMP program transitions from the acquisition HEMP program manager to an on-site HEMP program manager when the O&S phase begins. Development of the HM/HS plan, as described in 21.8.2.1, occurs before this transition. All other activities covered by 21.8.2.2 through 21.8.2.6 are performed under the supervision of the on-site HEMP program manager.

21.8.2.1 HM/HS plan development. The HM/HS plan is developed by the supporting activity for logistics during the design, construction, and C-E equipment installation phases. A preliminary version, covering HCIs provided under the building construction contract and in sufficient depth for maintenance during equipment installation only, should be available at the time of building acceptance. The final and approved plan will be required at the time of initial operating capability.

HM/HS is considered to include routine preventive maintenance, troubleshooting and repair, organizational hardness surveillance, periodic surveillance/reverification testing, spares/repair parts/special tools and test equipment, training, and configuration control. Using this definition, an HM/HS plan outline is provided in table XXXIII. The document is likely to be two or more volumes, and technical manual format is strongly encouraged.

The outline appears to be extremely formidable. However, commonalities among facilities hardened to MIL-STD-188-125 HEMP requirements are extensive. They all employ the same types of HCIs and, therefore, basic procedures for preventive maintenance, repair, and testing apply to all such facilities. The HEMP protection subsystems all operate according to the same principles and require similar training and configuration control measures. It is estimated from these facts that in excess of 75 percent of the information in the HM/HS plan for one MILSTD-188-125 site is transferable to the plan for another.

It is recommended that each military service establish organizational maintenance, periodic surveillance/reverification test, spares and special equipment, training, and configuration control policies. From these policies, a generic HM/HS plan for MIL-STD-188-125 HEMP-protected facilities should be generated. Adaptation of this generic plan to a particular site would then be a relatively straightforward task.

Preventive maintenance for a HEMP protection subsystem is simple and consists primarily of cleaning rf seals and waveguides, checking torques, and replacing ESAs as required. Periodic inspections are visual, and performance checks employ a SELDS or similar portable shielding effectiveness measurement instruments. Recommendations for these procedures are presented in section 20. Corrective maintenance procedures are somewhat more complicated, because required capabilities to perform the repair and make the subsequent performance measurements may not be resident in the O&S staff. Finally,

TABLE XXXIII. HM/HS plan outline.

HM/HS PLAN OUTLINE

I. INTRODUCTION - Identify the subject facility and state the purpose of the plan: provide an overview of the contents.

II. HEMP PROTECTION SUBSYSTEM DESCRIPTION – Provide a narrative and pictorial description of the HEMP protection subsystem, including the following items:

- A. Site plan
- B. Floor plan and elevation drawings, showing the location of the electromagnetic barrier and the protected volume
- C. Shield description including materials, thicknesses, joining methods, and selected assembly details
- D. List of barrier POEs and POE protective devices; provide selected details of protective device installations: provide manufacturers' data sheets for commercial HCIs in an appendix
- E. Provide descriptions and HCI lists for all special protective measures

III. PRINCIPLES OF OPERATION - Briefly describe the operation of the HEMP protection subsystem and its elements.

IV. ORGANIZATIONAL PREVENTIVE MAINTENANCE, TESTS, AND INSPECTIONS - Provide detailed procedures (see section 20) for all periodic maintenance. tests, and inspections to be performed by the O&S personnel, including the following items:

- A. HCI (or HCIs) on which the maintenance is to be performed
- B. Personnel requirements and skill levels
- C. Time required
- D. Tools and supplies required
- E. Frequency of maintenance
- F. Step-by-step instructions, including safety precautions and acceptability or pass/fail criteria

TABLE XXXIII. HM/HS plan outline (continued).

V. TROUBLESHOOTING AND REPAIR - Provide detailed procedures (see section 20) for troubleshooting and corrective maintenance including the following items:

A. HCI (or HCIs) on which the maintenance is to be performed

B. Capability requirements (organizational, base services, or contract)

C. Step-by-step instructions. including safety precautions

D. Quality assurance test procedures for the completed repair

VI. PERIODIC SURVEILLANCE/REVERIFICATION GENERAL TEST PLAN - Provide general procedures for periodic surveillance/reverification testing including the following information:

A. Organization for performing the tests

B. Procedures for scheduling

c. General test requirements such as types of measurements, sampling requirements, pass/fail criteria, and data disposition

D. A matrix indicating which HCIs should be tested in the first surveillance test, second test, etc.

VII. ORGANIZATIONAL SPARES, REPAIR PARTS, SUPPLIES, AND SPECIAL TOOLS AND TEST EQUIPMENT - Provide lists of items, sources, and recommended quantities to be maintained on site.

VIII. TRAINING PLAN - Provide training requirements for operators and maintenance staff members; materials for locally administered training should be provided with the training plan.

IX. CONFIGURATION CONTROL PLAN - Provide procedures for configuration control (see section 19).

X. INSTRUCTIONS FOR CHANGES - Provide instructions for implementing formal changes to the HM/HS plan.

service organizations equipped to perform the surveillance/reverification testing do not currently exist.

Most sites do not now have organizational spares and repair parts for facility HCIs. Until department policies are established on this issue, the following level of provisioning is recommended:

a. Cleaning kits, supplies, and repair parts for two years of normal maintenance on shielded doors

b. At least 200 percent spares for each type of rf gasket used in the HEMP protection subsystem

c. A minimum of 10 percent or at least one of each type of filter and ESA installed in the facility

No special tools, unless required for shielded door maintenance, are likely to be necessary. A SELDS and 400 MHz "sniffer," supportable by base electronics repair and calibration shops, are recommended.

Training should include awareness briefings for all site personnel and more extensive training for HEMP program managers and leading maintenance personnel. A videotape presentation will be adequate for the awareness course. Formal schooling, supplemented with on-the-job training, is suggested for the in-depth course.

An outline for the configuration control plan is presented and discussed in section 19.

21.8.2.2 Organizational hardness maintenance and surveillance. When the HM/HS plan is properly prepared, organizational hardness maintenance and surveillance is simply a matter of performing the prescribed actions in accordance with the written procedures. Preventive maintenance, visual inspections and performance checks are done at the designated times, and results are recorded. When an HCI failure occurs or a deficiency is found by surveillance, repairs are made and the appropriate QA test is conducted. If the repair or testing requires expertise or equipment not available on the site, the HEMP program manager will take the necessary steps to acquire outside assistance.

In the real world, however, HM/HS plans will not be perfect. Inspection intervals will be too long or too short, and procedures may lack sufficient detail. Situations not anticipated by the preparer of the plan will be encountered, and errors will be found. All improvements required in the HM/HS plan should be reported to the on-site HEMP program manager, who initiates the change proposal via established procedures.

HM/HS plan revisions will also be necessary as the result of facility modifications (see 21.8.2.6). The HEMP program manager should ensure that planning of the modification includes an element for updating the HM/HS plan.

Section 20 of this handbook describes the organizational preventive maintenance, corrective maintenance, inspections, and tests recommended for preserving hardness at a typical facility.

21.8.2.3 Periodic hardness surveillance/reverification testing. At intervals prescribed by the HM/HS plan, typically five to seven years, a qualified testing organization will perform hardness surveillance/reverification testing. The surveillance test is similar to a verification test, except that shield performance may be checked with the built-in monitor and SELDS rather than cw immersion.

Planning for the hardness surveillance/reverification test should begin approximately six months prior to the scheduled start of testing. The HEMP program manager should contact the organization designated to perform the test, and arrange for a site visit. The visit must include the following activities:

a. A thorough site inspection by personnel of the testing organization, accompanied by site O&S staff members. HEMP protection subsystem deficiencies identified during the inspection should be repaired before the start of testing.

b. A review of maintenance records and site modifications since the previous verification or reverification test. All HCIs installed subsequent to the last test should be noted and scheduled for performance measurements.

c. A discussion of coordination and scheduling. Needs for facility downtime should be established, so that appropriate arrangements can be made well in advance.

It is a common practice for the testing activity to provide a HEMP training session for site personnel, since many of the site staff members will have arrived after the last test program.

The testing organization will then prepare the detailed test plan. The test plan follows the same outline previously given for verification testing (see 21.7.2.1) and, in fact, much of the plan can be taken verbatim from the verification test plan or the last reverification test plan.

Approximately one month before the start of testing, another coordination meeting should take place. The test plan should be reviewed and approved at this meeting, and all

arrangements should be concluded. The testing is then conducted in accordance with the plan. The measurements will typically require three to five weeks.

At the conclusion of the test, a preliminary briefing on the results should be provided to the site commander. The testing organization will then prepare the test report in a format similar to that of a verification test report (see 21.7.2.3).

The HEMP program manager is responsible for the correction of site hardening deficiencies found by the surveillance/reverification test. Possible changes in organizational HM/HS to prevent future occurrences of the same or similar problems should also be considered.

21.8.2.4 Spare parts and special equipment. One section of the HM/HS plan will contain inventories of HCI spares, repair parts, and supplies to be maintained at the facility. A list of special tools and test equipment required for HM/HS will also be provided.

The HEMP program manager is responsible for ensuring that stocks are replaced when used and that special test equipment is maintained and calibrated. The replacement should have the same part number and be obtained from the same supplier as the original equipment, if possible. If the original item is no longer available, the HEMP program manager must ensure that the substitute is fully equivalent. As with other portions of the HM/HS plan, the HEMP program manager is also responsible for initiating change procedures when the parts or special equipment lists are found to need improvements.

21.8.2.5 HEMP training. One of the responsibilities of the HEMP program manager is to ensure that training is conducted in accordance with the HM/HS training plan. The requirements may vary somewhat from service to service, but they will typically include the following:

a. HEMP awareness briefings for all new personnel reporting to the facility staff; a locally administered videotape presentation will generally be used for this purpose.

b. More extensive training, by the department's schools command or with locally given courses, for HEMP program managers and leading maintenance personnel; this training should include practical, on-the-job experience.

c. Periodic training sessions on site, to reemphasize HEMP awareness and to address site-specific issues and problems.

Training materials for the incoming HEMP awareness briefing and course materials for maintenance training, if it is to be conducted on site, should be provided with the

HM/HS plan. The HEMP program manager is responsible for preparing or arranging the additional periodic sessions. The service centers for HEMP expertise and reverification testing organizations can sometimes supply instructors for these sessions.

21.8.2.6 Configuration control and facility modifications. Frequent facility modifications should be expected as improved equipment becomes available, older hardware becomes unsupportable, and missions and scenarios change. Configuration control requirements and methods, described in handbook section 19, are intended to cope with the changes while preserving HEMP hardness. The essence of this HEMP program manager responsibility is ensuring that hardness impacts are properly considered before any modification is implemented. Six criteria for determining if a construction change affects the HEMP protection subsystem are cited in 21.5.2.4, and they also apply during the O&S phase.

The HEMP program manager should review all proposed modifications for potential hardness impacts. When the possibility of degrading the protection exists, he should verify that the following have occurred:

a. Design of the modification is in accordance with MIL-STD-188-125 and has been reviewed by knowledgeable HEMP engineers.

b. Construction/installation activities are subject to HEMP supervision, and that appropriate QA and acceptance test requirements are levied and enforced.

c. Verification testing of affected parts of the system is conducted; when the change is evaluated to be minor, verification can be deferred until the next surveillance test.

d. All elements of the HM/HS plan are revised to reflect the modified configuration of the HEMP protection subsystem.

In summary, every modification with HEMP impact goes through the same phases as the original development project.

21.9 References.

21-1. O'Hara, J., P. Powers, M. Sanches, F. Balicki, and W. Herman, "Program Management Handbook on Nuclear Survivability," DNA-H-90-30, Defense Nuclear Agency, Alexandria, VA, November 1990.

21-2. "Military Standard – High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Tim-Urgent Missions," MILSTD-188-125 (effective), Dept. of Defense, Washington, DC.

21-3. "Military Construction Responsibilities," DoD Directive 4270.5 (effective), Dept. of Defense, Washington, DC.

21-4. "Defense Acquisition," DoD Directive 5000. I (effective), Dept. of Defense, Washington, DC.

21-5. "Defense Acquisition Management Policies and Procedures," DoD Instruction 5000.2 (effective), Dept. of Defense, Washington, DC.

21-6. Thompson, C., and R. Beaty, "Military Handbook for Hardness Assurance, Maintenance, and Surveillance (HAMS) Planning," DNA-TR-89-281, Defense Nuclear Agency, Alexandria, VA, September 1990.

21-7. "Implementation of the Planning, Programming, and Budgeting System (PPBS)," DoD Directive 7045.7 (effective), Dept. of Defense, Washington, DC.

21–8. "The Planning, Programming, and Budgeting System (PPBS)," DoD Directive 7045.14 (effective), Dept. of Defense, Washington, DC.

21-9. "Military Standard - Engineering Drawing Practices," MIL-STD-100 (effective), Dept. of Defense, Washington, DC.

APPENDIX A

SAMPLE CONSTRUCTION SPECIFICATIONS FOR THE HEMP PROTECTION SUBSYSTEM

FOREWORD

This appendix contains sample specifications for constructing a HEMP protection subsystem to meet the requirements of MIL-STD-188-125. These HEMP protection subsystem specifications will appear as one of the divisions in the construction specifications document for the total project. The intended purpose of the appendix is to illustrate the nature and depth of information that must be provided.

The U.S. Army Corps of Engineers and Naval Facilities Engineering Command are currently developing an official guide specification for a HEMP protection subsystem. When the guide specification becomes available, it will replace the material in this appendix.

The particular format and specific provisions in the sample specifications, except where they are taken directly from MIL-STD-188-125, should be considered only as examples. The key points to be noted include the following:

a. The obligations of the construction contractor are completely defined by the specifications and the drawings. The contractor must provide only those items and perform only those tasks explicitly required by the specifications and drawings.

b. Listing a document as an applicable publication does not invoke all requirements in that document. Only those invoked explicitly in subsequent specification provisions must be met.

c. The contractor must supply only those submittals that are explicitly required. The Government's right to approve or reject submittals must be explicitly reserved, where applicable.

d. Materials and components are required to have only those characteristics and meet only those performance requirements that are explicitly identified. Furthermore, many characteristics and performance requirements are ill-defined unless the methods of verifying compliance are also identified.

e. If a particular fabrication or installation method is required, it must be explicitly shown in the drawings or specified. Otherwise, the contractor is free to choose the method.

f. Specifying a performance requirement does not obligate the contractor to demonstrate compliance. If a test is required, it must be explicitly specified. If a particular test method is required, the method must be explicitly specified.

In summary, everything required must be shown in the drawings or written into the specifications.

The sample specifications contain material selections and numerous quantitative requirements that may not be applicable to every project. The shield in the sample specification, for example, is constructed from ASTM A36/36M carbon steel. The contractor's quality control plan must be delivered within 30 days after notice to proceed. Magnetically operated doors must function through 500,000 cycles without major adjustment, and the minimum acceptable insulation resistance for electrical filters is 1 MΩ. The materials and specific numerical values are intended to be reasonable, compatible with the hardware state-of-the-art, and consistent with the recommendations in this handbook. However, each of the choices should be critically reviewed for applicability before being included in the specifications for a particular facility.

Barrier acceptance testing is included as the last part of the sample specification. However, this handbook recommends that the acceptance testing be performed by a separate contractor, hired by the Government, rather than by the construction contractor. The sample specification does not include a requirement to develop the HEMP protection subsystem technical manual described in this handbook. Instruction manuals for hardness critical items and assemblies supplied by the construction contractor are specified, however; these manuals are intended to be used in developing the HM/HS plan.

10. GENERAL REQUIREMENTS FOR THE HEMP PROTECTION SUBSYSTEM

10.1 Applicable publications. The current editions of publications listed below form a part of this specification to the extent referenced. The publications are referenced by the basic designation only.

10.1.1 American Institute of Steel Construction (AISC) publications.

S326 - Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.

10.1.2 American National Standards Institute (ANSI) publications.

70 - National Electrical Code (NFPA).
77 - Recommended Practice on Static Electricity (NFPA).
78 - Lightning Protection Code (NFPA).
142 - Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE).
A2.4 – Standard Symbols for Welding, Brazing, and Nondestructive Examination (AWS).
A3.0 – Standard Welding Terms and Definitions Including Terms for Brazing, Soldering, Thermal Spraying, and Thermal Cutting (AWS).

A5.18 - Carbon Steel Filler Metals for Gas Shielded Arc Welding, Specification for (AWS).
C2 - National Electrical Safety Code (IEEE).
D1.1 – Structural Welding Code – Steel (AWS).
D1.3 – Structural Welding Code – Sheet Steel (AWS).
Z49.1 - Safety in Welding and Cutting (AWS).

10.1.3 American Society for Testing and Materials (ASTM) publications.

A36/A36M - Standard Specification for Structural Steel.

10.1.4 Military standards.

MIL-STD-22 – Welded Joint Design.
MIL-STD-100 – Engineering Drawing Practices.
MIL-STD-130 - Identification Marking of U.S. Military Property.
MIL-STD-188-124 – Grounding, Bonding, and Shielding for Common Long Haul/Tactical Communication Systems, Including Ground-Based Communication-Electronics Facilities and Equipments.
MIL-STD-188-125 - High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based Facilities Performing Critical, Time-Urgent Missions.

MIL-STD-202 - Test Methods for Electronic and Electrical Component Parts.
MIL-STD-220 – Method of Insertion-Loss Measurement.
MIL-STD-248 – Welding and Brazing Procedure and Performance Qualification.
MIL-STD-1261 - Arc Welding Procedures for Constructional Steel.

10.1.5 Military specifications.

MIL-B5087 - Bonding, Electrical and Lightning Protection, for Aerospace Systems.
MIL-T-10727 - Tin Plating, Electrodeposited or Hot-Dipped, for Ferrous and Nonferrous Metal.
MIL-F-15733 - Filters and Capacitors, Radio Frequency Interference, General Specification for.
MIL-P-26915 - Primer Coating, Zinc Dust Pigmented, for Steel Surfaces.

10.1.6 Military handbooks.

MIL-HDBK-423 - High-Altitude Electromagnetic Pulse (HEMP) Protection for Fixed and Transportable Ground-Based C^4I Facilities.

10.1.7 Federal specifications.

FF-W-84 - Washers, Lock (Spring).
FF-S-325 – Shield, Expansion; Nail, Expansion; and Nail, Drive Screw (Devices, Anchoring, Masonry).
FF-B-588 - Bolt, Toggle; and Expansion Sleeve, Screw.

10.2 General requirements. The high-altitude electromagnetic pulse (HEMP) shield shall be a steel single-skin design with electrical shielding metal welded to the frame. The HEMP protection subsystem shall consist of the shield with shielded doors and shielded covers at personnel and equipment accesses, waveguide-below-cutoff protection for piping and ventilation points-of-entry (POEs), and filters and electronic surge arresters installed on penetrating electrical conductors. Fittings and hardware necessary for a complete and operable HEMP protection subsystem shall be provided. Where two or more units of the same type, class, and size of equipment are required, these units shall be products of a single manufacturer. The work shall be performed under the fill-time direct supervision of personnel who are experienced in the installation of all-metal welded HEMP protection

subsystems and have supervised the installation of not fewer than five such systems that have operated satisfactorily.

The ability to maintain high shielding effectiveness for long term use with minimum maintenance shall be stressed throughout the construction and erection of the specified HEMP protection subsystem. Particular attention shall be paid to the total project, so that the installation of the doors and covers, piping and ventilation penetrations, electrical services, and connector panels do not reduce the required shielding effectiveness.

10.2.1 Scope. This section specifies the construction and quality assurance requirements of the HEMP protection subsystem defined by the approved construction drawings. The scope of the contract includes the following general tasks:

a. Construct a continuous welded steel HEMP shield.

b. Provide and install all shielded doors, access panels, and accessories.

c. Provide proper shield terminations for all mechanical penetrations of the shield by pipes and structural elements.

d. Provide and install all welded waveguide-below-cutoff arrays and honeycomb air vent filters.

e. Provide and install all HEMP filter/surge arrester assemblies, including enclosures, for all electrical penetrations of the shield.

f. Provide and install all shielded conduit runs, junction boxes, and pull boxes.

g. Provide HEMP protection for mission-essential equipment located outside the HEMP shield and identified in the system drawings. (An example of this type of equipment is mission-essential condensing units.)

h. Provide reliable components, installed in a manner that ensures maintainability and testability.

i. Provide quality control supervision to include the review of shop drawings of the interfacing trades, in-process inspection, and testing of the entire HEMP protection subsystem.

j. Provide final acceptance testing of the completed HEMP protection subsystem by a Government-approved testing agency.

10.2.2 Performance requirements. The HEMP protection subsystem is designed to provide protection for specified critical electronics equipment. The protection subsystem is essential to the function of the facility, and the quality and installation of its components are key considerations under the quality assurance requirements of this contract. If the specifications in this part conflict with the specifications in other parts, notification shall be provided to the Contracting Officer in writing. Pending Contracting Officer resolution, this part shall govern.

10.2.2.1 Compliance with MIL-STD-188-125. The completed HEMP protection shall comply with all construction and performance requirements of MIL-STD-188-125, including shielding effectiveness and pulsed current injection (PCI) requirements when measured by the techniques prescribed in MIL-STD-188-125. In the event of conflict between this specification and MIL-STD-188-125, notification shall be provided to the Contracting Officer in writing. Pending Contracting Officer resolution, this specification shall govern.

10.2.2.2 warranty. The HEMP protection subsystem shall be warranted by the contractor to satisfy all performance requirements for at least one year, when maintained in accordance with procedures supplied by the contractor. The performance requirements apply to the finished structure with all electrical and mechanical penetrations installed and operating.

10.2.3 Shielding contractor.

10.2.3.1 Qualifications. The HEMP protection subsystem shall be provided by an experienced firm that is regularly and successfully engaged in the installation and/or manufacturing of equally complex HEMP protection subsystems. The Contracting Officer may reject any proposed shielding contractor who cannot show documented evidence of five years experience in the design, construction, and testing of electromagnetic shielding of similar complexity.

10.2.3.2 Responsibilities. All shielding work and associated work on the HEMP protection subsystem shall be the responsibility of a designated shielding contractor. The HEMP protection subsystem specified herein is detailed in the drawings. In addition, materials that are integral with and part of the HEMP protection subsystem are specified in other parts of this specification. It shall be the responsibility of the shielding contractor to supply and install all materials necessary for a complete, tested, and operational HEMP protection subsystem. The shielding contractor shall verify all building dimensions by measurements in the field, as necessary, before fabrication. The HEMP shield shall be fabricated to allow maintenance and repair throughout the life of the facility.

10.2.3.3 Coordination. The contract drawings indicate the extent and general locations and arrangements of shielding materials and HEMP protection features. The contractor shall coordinate the sequencing of construction; the selection of shielding materials, attachments, and accessories; and the location and size of shielding penetrations and protection devices with the affected trades. If conflicts necessitating departures from the contract drawings occur, details of the departures and reasons therefore shall be submitted to the Contracting Officer for approval prior to installation.

It is the responsibility of the HEMP protection shielding contractor to warn all trades against unauthorized penetrations. Any repair work resulting from incompatibilities, shield discontinuities, unauthorized penetrations, or other adverse changes in the shielding shall be at no cost to the Government.

10.3 Components.

10.3.1 Shield. The HEMP shield in the facility shall be constructed of sheet steel, conforming with ASTM A36/A36M and with a minimum thickness of 5 mm (0.2 in). All welding of the shield shall be in conformance with the provisions of section A.20.

10.3.2 Penetrations. Shield penetrations are shown on the drawings with HCI symbols per MIL-STD-100 and are listed on the Shield Penetration Schedule, Drawing No. ____, Sheet ___. No penetrations of the HEMP shield other than those listed on the Shield Penetration Schedule shall be allowed without prior, written approval of the Contracting Officer. All penetrations of the shield shall have special treatments as indicated in the plans and specifications. No other penetrations or penetration treatments shall be allowed without prior, written authorization of the Contracting Officer. Extreme care shall be exercised to prevent accidental penetration of the shield when installing any subsequent features. Any such penetrations shall be repaired at no cost to the Government.

10.3.2.1 Doors. All radio frequency (rf) shielded doors shall be supplied as complete assemblies that include frames and hardware, shall comply with all requirements stated in A.30, and shall be welded into place in accordance with provisions of that part. All such doors shall be equipped with sensors to indicate when open. Doors shall be interlocked where indicated to prevent simultaneous opening.

10.3.2.2 Waveguide-below-cutoff penetrations. All waveguide-below-cutoff piping and ventilation penetrations shall have a minimum aspect ratio (length to greatest inner dimensions) of 5:1 and a maximum diameter of 10 cm (4 in), as shown on the drawings. These penetrations may occur singly (as in generator exhausts) or in multiples (as in air

vents). All waveguide-below-cutoff penetrations shall comply with all requirements stated in A.40 and shall be welded into place in accordance with provisions of that part.

10.3.2.3 Electrical filters and electronic surge arresters (ESAs). All conductive electrical signal, control, and power penetrations shall be treated with filters and surge arresters. The filters, ESAs, and enclosures shall comply with the requirements stated in A.50 and shall be installed in accordance with the drawings, contract specifications, and manufacturer's specifications.

10.3.2.4 Shielded conduit system. The conduits that connect the shields in the facility to exterior equipment or shields in other facilities are a part of the HEMP protection subsystem. The shielded conduit system, including pull boxes and terminations, shall be designed to provide at least the same level of rf attenuation as is provided by the HEMP shields in the facility, as detailed in A.60.

10.3.2.5 Special protective components. Shielded enclosures and other hardening devices installed as special protective measures shall comply with the requirements of the drawings and A.70.

10.3.3 Standard products. All materials and equipment shall be the latest standard products of the manufacturer regularly engaged in the manufacture of these products. All materials shall be new and in strict conformance with all requirements of the drawings and specifications.

10.3.4 Standards compliance. Where equipment or materials are specified to conform to requirements of standards published by industrial organizations, such as ASTM or ANSI, proof of such conformance shall be provided to the Contracting Officer. The label and listing of the specified organization will be acceptable evidence. In lieu of the label or listing, submit a written certificate from an acceptable testing organization, adequately equipped and competent to perform such services, stating that the items have been tested and that the units conform to the specified standards.

10.3.5 Making. All components and assemblies provided under this section shall be marked in accordance with MIL-STD-130 and as specified herein. Markings shall include **HCI** identifications as shown in the drawings.

10.3.6 Reliability. Unless otherwise specified herein, all components and assemblies provided under this section shall have mean times between failure of at least five years when maintained in accordance with procedures required by A.1O.7.9.

10.4 Delivery and storage. Materials shall be delivered to the job site in an undamaged condition. Materials shall be stored to insure proper alignment, ventilation, and drainage, and shall be protected against dampness before and after delivery. Materials shall be stored under cover in a well-ventilated enclosure and shall not be exposed to extreme changes in temperature and humidity that could cause damage. Materials shall not be stored in the building until concrete and masonry are dry. Defective or damaged materials shall be replaced by the contractor at no additional cost to the Government. Damaged or misaligned materials shall be rejected. Contractors shall phase the installation of the various HEMP protection subsystem components so as to prevent damage during construction. The contractor shall be responsible for adequately protecting HEMP protection elements whether they are stored or installed.

10.5 Installation. Assembly and installation of all materials and components provided under this section shall be in accordance with the approved shop drawings and as specified herein. All hardness critical processes shall be defined in the shop drawings with **HCP** notations and drawing notes required by MIL-STD-100, and the procedures shall be strictly followed.

10.5.1 Workmanship. All work required under this section shall be performed in a professional manner and in accordance with accepted industry standards. All fabrication and assemblies shall be of good quality, uniform in appearance, and free of defects that will affect life or serviceability.

10.5.2 Maintainability and testability. The HEMP protection subsystem provided under this section shall be maintainable and testable. Access for inspection, maintenance, and testing shall be provided as shown in the drawings. Access covers shall be constructed for safety and ease of removal and reinstallation. Built-in test features shall be provided as shown in the drawings.

10.5.3 Corrosion control. All materials, components, and assemblies provided under this section shall be free of rust and corrosion. Corrosion protection measures shall be provided as shown in the drawings and specified herein. Conditions that promote corrosion, such as exposure to weather and moisture accumulations, shall be prevented.

10.6 Quality control. The shielding contractor shall be responsible for all quality control including component testing, in-progress testing, and acceptance testing for the HEMP protection subsystem. The contractor shall establish a quality control program to ensure compliance with contractual requirement: and shall document the program in the quality control plan. The contractor shall maintain quality control records for all construction operations required under this part, and copies of these records shall be furnished to

the Government as required in CONTRACTOR QUALITY ASSURANCE and in SPECIAL PROVISIONS. The contractor shall provide the services of an independent testing laboratory or consultant, approved by the Contracting Officer, to perform the acceptance testing. All deficiencies shall be corrected at no cost to the Government.

10.6.1 General quality control requirements.

10.6.1.1 Test procedures and results. All required quality assurance testing shall be documented with test procedures and test reports, as required by A.10.7.6 and A.1O.7.7 of this specification. It is emphasized that tests must be performed on actual units that are delivered and installed, unless type testing is specified, and that actual test data shall be supplied to the Contracting officer. Certifications of specification compliance, without the supporting data, will not satisfy these requirements.

10.6.1.2 Notification of inspections and tests. The contractor shall notify the Contracting Officer at least 14 days before the performance of specified tests, except that notification before tests outside the continental United States shall be at least 30 days before the performance of tests. The Government reserves the right to witness all required testing.

10.6.1.3 Site visits. Personnel from Government agencies and contractors will be making random, but announced, visits to observe HEMP testing and quality assurance program execution and to monitor progress of construction of the HEMP protection subsystem. All visitors will be identified by the Contracting Officer or a designated representative.

10.6.1.4 Additional Government testing. At its discretion, the Government may conduct additional testing to verify compliance with specification requirements. Such tests will be performed in a manner that does not interfere with contractor activities and will not subject components or assemblies to stresses that exceed specified limits. The Government will notify the contractor of the nature and planned time of conduct of these tests, and the contractor may witness them.

10.6.2 Remedial action. If any component or assembly fails to meet the specified requirements, as shown by required quality assurance tests or additional tests by the contractor or Government, the contractor shall replace the defective item, repair the defective installation, or take other actions necessary to achieve acceptable performance. These remedial actions shall be taken at no additional cost to the Government.

10.7 Submittals. In accordance with SPECIAL PROVISIONS, the contractor shall submit data for the following items required by this paragraph. The Government reserves the right to reject or disapprove submittals that do not comply with all requirements of these specifications.

10.7.1 Qualifications.

a. Identification and credentials of the HEMP protection shielding contractor establishing evidence of five years experience involving the design, construction, and testing of HEMP protection subsystems of a similar type shall be submitted within 15 days after notice to proceed.

b. Identification and credentials of the on-site HEMP protection subsystem supervisors and quality control specialists showing requisite experience in the construction of other HEMP protection subsystem projects that have achieved the shield attenuation requirements listed herein shall be submitted within 15 days after notice to proceed.

c. Identification and credentials of vendors, catalog cuts, and manufacturer's data for shielded doors, electrical filters, ESAs, and waveguide-below-cutoff penetration protection devices shall be submitted within 60 days after notice to proceed.

d. Identification and credentials of the independent testing agency or consultant who will perform the acceptance testing shall be submitted at least 90 days before the start of testing.

10.7.2 Shop drawings. Shop drawings for the HEMP protection subsystem shall be submitted for Contracting Officer approval in accordance with requirements in SPECIAL PROVISIONS. The shop drawings shall consist of fabrication drawings, assembly drawings, and installation drawings. Manufacturer's descriptive and technical literature, catalog cuts, and installation instructions shall be provided for all purchased components. All hardness critical items and hardness critical processes shall be identified on the shop drawings with $\boxed{\textbf{HCI}}$ and $\boxed{\textbf{HCP}}$ symbols, respectively, in accordance with MIL-STD-100. Welding and brazing terms and symbols shall be in accordance with ANSI/AWS A2.4 and ANSI/AWS A3.0.

Fabrication drawings shall provide a complete list of parts and materials, sizes, arrangements, and methods of fabrication. Assembly drawings shall provide a complete list of components and materials, a shield penetration schedule, a hardness critical item list, and equipment locations and layouts. The top-level installation drawings shall indicate the sequence of construction, coordination with the work of other trades, and any other information to demonstrate that the HEMP protection subsystem will function as a complete

system. Installation detailed drawings shall show components and materials, fastenings, clearances, and installation methods including welding procedures.

The shop drawings shall have been approved by a professional structural engineer and shall bear his or her seal.

10.7.2.1 Shield shop drawings. Shield details shall be provided in shop drawings within 60 days after notice to proceed. The shop drawing shall provide a complete list of shield materials and shall show all assembly and erection details and processes. All hardness critical items and hardness critical processes shall be marked in accordance with MIL-STD-100.

Shield details shall include, but not be limited to, the following:

a. Shield materials and layouts

b. Complete details of seams and joints

c. Welding materials and procedures

d. Connections from the shield to supports, backing plates, and anchorage

e. Connection details from the shield to the grounding grid system

f. Penetration designations, locations, and type of protection for all shield penetrations

g. Attachments of shielded door and frame assemblies and equipment access covers

h. Attachments of waveguide-below-cutoff devices for piping and ventilation penetrations

i. Attachments of filter/ESA assemblies and shielded conduits for electrical penetrations

10.7.2.2 Ground system shop drawings. Connection details for the HEMP protection subsystem and the electrical power ground system to the ground grid system shall be provided in shop drawings within 60 days after notice to proceed.

10.7.2.3 Shielded door shop drawings. Shop drawings, prepared in accordance with MIL-STD-100, for each type of rf shielded door, threshold protection ramp, and access panel shall be submitted within 60 days after the notice to proceed. These shop drawings shall provide a complete list of materials. They shall identify arrangements, thicknesses, size of parts, construction fastenings, clearances, door weight, part number, assembly and erection details, and necessary connections to work of other trades. Shop drawings shall

include catalog data for all manufactured items (e.g. hinges, bearings, gaskets, seals). Approved shop drawings are required before fabrication can begin. The shop drawings shall include:

a. Complete details of construction for doors and frames, including hardware and shielding provisions

b. Complete layout and details of the controls, interlocks, and alarms for shielded doors

c. Detailed information for connecting the door and frame assemblies for hinged and sliding doors to the structure and to the basic building system

10.7.2.4 Waveguide-below-cutoff penetration shop drawings. Shop drawings for waveguidt-below-cutoff (WBC) POE protective devices shall be submitted within 60 days after notice to proceed. The drawings shall show the following information:

a. WBCs with weld plate-Size of plate, location and size of opening, method of cutting opening, welding procedures, and manufacturer's shop drawings (if applicable) showing all details and methods of construction

b. WBCs without weld plate-The location and size of opening, method of cutting opening, and welding procedures

10.7.2.5 Filter/ESA assembly shop drawings. The filter/ESA assembly shop drawings shall include a complete list of equipment and materials, including the manufacturer's descriptive and technical literature, catalog cuts, and installation instructions. Shop drawings shall also contain complete wiring and schematic diagrams for the equipment furnished, equipment layout, and any other details required to demonstrate that the assembly has been coordinated and will properly function as a unit. Installation details shall show the location of each POE and the method of penetrating the shield. These shop drawings shall be submitted within 60 days after the notice to proceed.

10.7.3 Quality control plan. The contractor's quality control (QC) plan shall be submitted for Contracting Officer approval within 30 days after notice to proceed. As a minimum, the plan shall include:

a. A description of the contractor's organizational structure, indicating the manner in which QC is integrated into job site management

b. The names, positions, and qualifications of all QC personnel or organizations and their specific responsibilities

c. The manner, methods, procedures, and techniques to be employed in the execution of the daily inspections and tests

d. A sample of the format that the contractor proposes to use for the daily QC report (see A.10.7.4 for details of daily QC report requirements)

e. The location and description of all testing facilities and equipment to be used

f. Procedures for control, submittal, and checking subcontractor submittals as required

The QC plan shall establish the general framework of the quality assurance program, and the detailed test procedures (see A.1O.7.6) shall be provided as appendices. Detailed test plans are required for in-progress testing of welds; for the complete (empty) shield effectiveness survey; for factory and in-place testing of shielded doors, waveguides and waveguide panels, filters, surge arresters, rf enclosures, and conduits; and for final acceptance testing. Test plans shall be submitted for Contracting officer approval at least 30 days before the scheduled start of testing.

10.7.4 Daily QC report requirements. Specific test report forms shall be submitted for approval at least 10 working days prior to the first time they are to be used. Legible copies of the daily "Construction Quality Control Report" shall be maintained by the contractor at the project site at all times, and the original copies of the inspection reports shall be delivered to the Contracting Officer on the work day following the date of the report. The daily inspections shall include observation of the type of work being performed during the report period and such other items as required to assure adequate quality control. Results of all inspections and tests performed by the contractor, in accordance with the technical provisions, shall be attached to the daily Construction Quality Control Report.

10.7.5 Manufacturer's certificates of compliance. (To be submitted when materials are received at the job site.) These certificates shall certify that the materials listed below conform to the requirements of this specification. Certifications shall be provided for the following materials and components:

a. Shield materials

b. Welding filler materials

c. rf shielded doors and access panels

d. Waveguide-below-cutoff POE protective devices

e. Electrical filters

f. Electronic surge arresters

10.7.6 Test plans and procedures.

10.7.6.1 Acceptance test plan and procedures. A detailed test plan and procedures for acceptance testing shall be submitted for approval to the Contracting Officer. The acceptance test plan and procedures shall include, but not be limited to, the following:

I. INTRODUCTION – Identify the facility to be tested and state the test objectives; provide an overview of the tests to be performed.

II. FACILITY DESCRIPTION - Provide a site plan, a floor plan of the protected volume, a list of shield POEs and the POE protective devices, and a list of special protective measures installed; provide a narrative description as required.

III. SHIELDING EFFECTIVENESS TEST PROCEDURES – Provide the following information:

   a. Plan and elevation drawings identifying plane wave and magnetic field test areas; identification of electric field test points, when required

   b. Specific test frequencies

   c. Test equipment identification by manufacturer, model, and serial number

   d. Detailed calibration and test procedures

   e. Procedures for marking, repair, and retest of defects

   f. Deviations from requirements of appendix A of MIL-STD-188-125

IV. PULSED CURRENT INJECTION TEST PROCEDURES – Provide the following information:

   a. Identification of POE protective devices to be tested by function and manufacturers' part number; attach manufacturers' data sheets in an appendix

   b. Test points and injection levels

   c. Simulation and data acquisition equipment identification by manufacturer, model, and serial number

   d. Detailed calibration and test procedures

   e. Deviations from requirements of appendix B to MIL-STD-188-125

V. TESTS OF SPECIAL PROTECTIVE MEASURES - Provide descriptions of the SPMs to be tested, locations of test points, and identification of simulation and data acquisition equipment by manufacturer, model, and serial number; provide detailed calibration and test procedures.

VI. DATA MANAGEMENT - Provide the following information:

a. Data quality control procedures, including acceptability criteria

b. Data processing requirements and algorithms

c. Procedures for identifying and preserving data

d. Pass/fail criteria

VII. SAFETY PLAN - Identify test hazards and procedures for protection of personnel and equipment.

VIII. SECURITY PLAN – Outline procedures for protection of classified data; omit when all data will be unclassified.

IX. TEST MANAGEMENT – Identify test participants, by agency or company, and responsibilities; provide test schedule.

Testing shall not commence without approval of the test procedures by the Contracting Officer.

10.7.6.2 Other test plans and procedures. Detailed test plans/test procedures for in-progress testing and quality assurance testing shall be provided to the Contracting Officer. The plan shall identify personnel, test equipment, methods, and specific test points and frequencies. The general test procedures shall include a description of how they will be performed as part of the in-progress and quality assurance testing to verify compliance with the requirements specified herein. Detailed procedures shall identify the system configuration for testing, instrumentation to be used, data requirements, test point locations, and measurement and calibration procedures. Testing shall not commence without approval of the test procedure by the Contracting Officer.

The test procedure shall include, but need not be limited to:

I. INTRODUCTION AND SCOPE

a. Statement indicating the purpose of the procedure and its relationship to the HEMP protection requirements

b. A list of all tests to be performed

c. The test location

II. APPLICABLE DOCUMENTS

a. Military

b. Company

c. Other

III. GENERAL

a. Description of the tests

b. Test equipment calibration procedure and traceability to the National Institute of Standards and Technology

IV. TEST PROCEDURES

a. Block diagram depicting test setup for each test method

b. Specific test equipment used in performance of the tests

c. Detail procedures showing placement and orientation of antennas or probes, test frequencies, selection of test points, data to be recorded, and success criteria

V. TEST DATA SHEETS

a. Examples of the test data sheets for all tests

VI. OUTLINE OF TEST REPORT

10.7.7 Test reports. (To be submitted within 15 days after completion of the test.) In-factory, in-process, and acceptance test reports shall be submitted to the Contracting Officer. See the applicable classification guide for information regarding the security classification of test reports.

10.7.7.1 Acceptance test reports. The report of HEMP protection subsystem acceptance testing shall include, but not be limited to, the following:

I. INTRODUCTION – Identify the facility tested and state the test objectives; reference the test plan.

II. DEVIATIONS FROM THE TEST PLAN - Identify all deviations from the test plan and provide rationale for these departures.

III. DATA – Provide copies of all measured and processed results. All data must be annotated to permit identification of the measurement location, test conditions, and conversions to engineering units.

IV. DATA SUMMARY – Provide a succinct data summary, in tabular form, which characterizes the measured results.

V. PASS/FAIL CONCLUSIONS

10.7.7.2 Other test reports. HEMP protection subsystem test reports other than the acceptance test report shall be in the format described in the approved test plan and procedures.

10.7.8 Instruction handbook. Two copies of an instruction handbook shall be supplied with the HEMP protection subsystem. The handbook shall contain:

a. A complete set of assembly drawings

b. The prescribed methods for welding panels, making electrical bonds and other attachments to the shield, and installing protection devices for POEs penetrating the shielding material without degrading the attenuation characteristics

c. A schedule of recommended hardness maintenance procedures, including preventive maintenance, inspections and corrective maintenance repairs and tests, to ensure continuous HEMP protection (see A.10.7.9)

The handbook and drawings shall be assembled in a washable vinyl-covered binder. One preliminary draft copy of the handbook shall be submitted for approval with the shop drawings.

10.7.9 Hardness maintenance procedures. Procedures to maintain the HEMP protection subsystem and allow the contractor's warranty to remain in effect shall be submitted to the Contracting Officer with the shop drawings. Revisions of the maintenance procedures, if required by as-built conditions, shall be submitted prior to performance of the final shield acceptance test.

20. HEMP SHIELD (See handbook section 8)

20.1 General requirements. The HEMP shield, exclusive of its penetrations, shall be a continuous steel enclosure, closed on all wall, ceiling, and floor surfaces. All seams and joints between adjacent steel sheets shall be continuously welded. Welding shall be performed by qualified welders, using the metal-inert gas (MIG) method, unless otherwise required by the drawings. Fabrication and erection of the shielded enclosure shall comply with applicable requirements of AISC S326.

The shield will be subjected to heavy, moveable, live floor loads during the installation of equipment. Adequate structural strength and permanent rf sealing of all seams is required to meet the total specification and usage.

20.1.1 Performance requirements. The HEMP shield, when closed by the installation of the penetration protection treatments specified in A.30 through A.60, shall meet the shielding effectiveness requirements of MIL-STD-188-125.

20.1.1.1 warranty. The HEMP shield, not including the penetration protection treatments, shall be warranted by the contractor to provide the required shielding effectiveness for a period of at least 15 years when maintained in accordance with the procedures supplied under A.20.2.6.

20.1.2 Qualifications.

20.1.2.1 HEMP protection shielding contractor. Qualification of the HEMP protection shielding contractor shall be in accordance with A.10.2.3.1. The shielding contractor shall be responsible for providing all required materials and for all HEMP shield assembly work required under this part.

20.1.2.2 Qualification of welders. Welding shall be performed by certified welders. Before assigning welders to work covered by this part of the specifications, the contractor shall identify welders to be employed. Certification shall be provided that each welder has passed qualification tests in the processes specified in ANSI/AWS D1.1, section 5; MIL-STD-248; and as required by the Contracting Officer. The contractor shall require a welder to retake the tests when, in the opinion of the Contracting Officer, the work of said welder creates a reasonable doubt as to that welder's proficiency. Tests, when required, shall be conducted at no additional expense to the Government. Recertification of the welder shall be made to the Contracting Officer only after the welder has taken and passed the required tests.

The Contracting Officer may require test specimens to be cut from any location in any joint. All sections of welds found to be defective shall be chipped, ground, or cut to the base metal and properly rewelded before proceeding with the work. Should any two test specimens cut from the work of any welder show strengths less than that of the base metal, it will be considered evidence of negligence or incompetence and such welder shall be permanently removed from the work. When specimens are removed from any part of an assembly, the members shall be repaired with joints of the proper type at no additional cost to the Government. The repair shall be of a quality to maintain shielding effectiveness and to develop the full strength of the members and joints with peenings as necessary to relieve residual stress.

20.1.2.2.1 Welder identification. Each welder, welding operator, or tacker shall be assigned an identifying number, letter, or symbol that will be used to identify all welds made by that individual. Each welder, welding operator, or tacker shall apply the identifying symbol adjacent to the weld by means of a rubber Stamp felt-tipped marker with waterproof ink, or other method that does not indent the metal. In the case of seam welds, the identification mark shall be adjacent to the weld at 1 m (3.3 ft) intervals. Die stamps or electric etchers shall not be allowed.

20.1.3 Marking. The HEMP shield shall be marked with an [HCI] identification as shown in the drawing. The [HCI] identification may be applied by painting or with plastic tags affixed to the shield with epoxy.

20.2 Submittals. The following submittals for the HEMP shield shall be submitted to the Contracting Officer in accordance with A.10.7.

20.2.1 Qualification data.

20.2.1.1 HEMP protection shielding contractor. Within 15 days after the notice to proceed, the construction contractor shall provide the data identifying HEMP protection shielding contractor and presenting supporting experience information in accordance with A.10.7.1. The information shall be of sufficient detail to demonstrate the ability to meet the requirements of this part. As a minimum, it shall include the following:

a. Statement of capabilities including the number of employees, years in business, and contract experience.

b. List of at least five installations of comparable size and complexity that have been successfully constructed within the last 10 years. Names and telephone numbers of contacts that can verify satisfactory performance shall be provided.

20.2.1.2 Welder qualification certificates. Qualification certificates for all qualified welders shall be provided to the Contracting Officer before the welder is permitted to work on the HEMP shield. Welder disqualification notices shall be provided within 24 hours of disqualification.

20.2.2 Shop drawings. Shop drawings for the HEMP shield and the ground system shall be submitted in accordance with A.10.7.2, A.10.7.2.1, and A.10.7.2.2. The shield shop drawings shall show the type of materials, welding methods, and assembly details. The ground system shop drawings shall show the ground grid and connections.

20.2.3 Certificates of compliance. Certificates of compliance shall be submitted by the contractor to show that materials used for HEMP shield construction comply with the requirements of this part.

20.2.4 Test plans and procedures. Detailed test plans and procedures for the in-progress weld inspection and test program, for the shielding effectiveness survey of the closed (empty) shield, and for acceptance testing of the completed HEMP shield shall be submitted. Test plans and procedures shall be submitted for approval at least 30 days before the planned date of conduct.

20.2.5 Test reports. Test reports for the shielding effectiveness survey and acceptance testing of the HEMP shield shall be submitted within 15 days after completion of the test in accordance with A.10.7.7. Weld inspection and test reports shall be submitted with the daily QC report.

20.2.6 Operation and maintenance instruction manuals. Operation and maintenance instructions for the HEMP shield shall be included in the HEMP protection subsystem handbook and maintenance manual required by A.10.7.8 and A.10.7.9, respectively. Maintenance procedures shall include, but not be limited to, inspection methods and intervals and instructions for repair and replacement.

20.3 Requirements.

20.3.1 Materials.

20.3.1.1 Shield material. The steel plates used to construct the HEMP shield shall conform to ASTM A36/A36 M. The sheets shall be sized for optimum fabrication and installation and shall have a minimum thickness of 5 mm (0.2 in) or 6.4 mm (0.25 in), as shown in the drawings. They shall be treated or provided with factory-applied coatings for protection from corrosion as shown in the drawings. The sheets shall be flat or formed

into the required shapes, as shown in the drawings, and shall have no bends, kinks, or other deformities. The steel shall be free of mill scale and shall be cleaned and degreased prior to installation. Rusty or dirty steel shall not be installed.

20.3.1.2 Welding materials. The HEMP shield shall be assembled using MIG welding, unless otherwise required by the drawings. The HEMP protection subsystem contractor shall select welding wire or rods for shield seam welds in accordance with ANSI/AWS D1.1 and ANSI/AWS A5.18.

20.3.1.3 Miscellaneous materials and parts. Materials and parts necessary to complete each item, even though the work is not definitely shown or specified, shall be supplied. Miscellaneous bolts and anchors, supports, braces, and connections necessary to complete the miscellaneous metal work shall be provided. The necessary lugs, rebars and brackets shall be provided so that work can be assembled in a neat and workmanlike manner. Holes for bolts and screws shall be drilled or punched. Poor matching of holes will be cause for rejection. Thickness of metal and details of assembly and supports shall give ample strength and stiffness. Required anchors and washers shall conform to specifications as follows:

a. Anchors: Federal Specifications FF-B-588 and FF-S-325

b. Washers: Federal Specifications FF-W-84

20.3.2 Penetrations.

20.3.2.1 Penetration identification. As part of the work of this section, the contractor shall carefully examine the shield drawings and penetration schedule to identify the number, types, locations, and sizes of the planned penetrations. The contractor shall also review the mechanical, electrical, and structural drawings to ensure consistency. Within 30 days after the notice to proceed, the contractor shall submit to the Contracting Officer a letter certifying that this review has been performed. The letter shall identify any discrepancies and shall recommend changes necessary to ensure the integrity of the HEMP protection subsystem.

20.3.2.2 Penetration fixtures. The contractor shall provide the necessary openings in the HEMP shield and all required fixtures for installing penetration protection devices specified in A.30 through A.60.

20.4 Delivery and storage. All materials required for assembling the HEMP shield shall be delivered to the job site in an undamaged condition. Materials shall be stored

under cover and shall be protected from physical damage and environmental conditions that could cause damage or corrosion. Defective or damaged material shall not be installed, and they shall be replaced by the contractor at no additional cost to the Government.

20.5 Installation.

20.5.1 Sequence of installation. Erection of the steel shall be sequenced to minimize sheet warpage. Shop drawings shall show erection details and sequence of erection, and shall clearly indicate the methods to be used to ensure shield integrity. All shielding materials and components must have passed final inspection prior to installation.

20.5.1.1 Placement of floor shield. Placement of the floor shield shall not commence until at least 14 days after the pouring of the floor slab.

20.5.1.2 Protection during fabrication. The contractor shall provide a stable temperature and humidity environment (using plastic sheeting, environmental control equipment, etc.) for the shield installation before commencing shield fabrication.

20.5.1.3 Covering of shield work. In addition to the contractor's quality control of materials and workmanship, the contractor shall notify the Contracting Officer at least 10 working days prior to covering or enclosing any shield work. This will give the Contracting Officer adequate time to inspect systems (if so desired) and witness any covering or enclosing of the shield work.

20,5.2 Construction control. The HEMP protection subsystem contractor shall assign a job supervisor with overall responsibility for proper fabrication and erection of the HEMP shield. The supervisor or a designated representative shall be present whenever shielding contractor or subcontractor personnel are performing work on the shield. The supervisor or a designated representative shall also monitor the work of other trades, when such work has the potential to damage or degrade the performance of the HEMP shield.

The job supervisor shall be responsible for informing other trades of the shielding effectiveness requirements and the prohibition on unauthorized penetrations of the shield. Penetrations not listed on the Shield Penetration Schedule shall be removed, unless a change order is approved by the Contracting Officer, and shield damage shall be repaired by the contractor at no additional cost to the Government.

20.5.3 Welding for seam integrity. The steel sheets shall be assembled into a solid rf-tight shield by continuous welding of all seams. If butt-welded seams are specified, all seams shall be made over steel backing material. Where seams fall over steel structural

members, these members may be used as the backing material. Where backing material is required, it shall overlap the shielding material by at least 2.5 cm (1 in) on both sides of the weld and shall be at least as thick as the sheets being welded. To the maximum extent feasible, seams shall be avoided at the intersections of walls and the intersections of walls and ceilings and walls and floors. Enclosure corners may be formed and welded before installation to minimize welding and assembly difficulty and to enhance seam integrity.

20.5.3.1 Welding method. The HEMP shield shall be assembled using MIG welding, unless otherwise required by the drawings. Welding techniques shall be in accordance with ANSI/AWS D.1.1, sections 4 and 5, and MIL-STD-1261. Workmanship shall be in accordance with ANSI/AWS D1.1, section 3. Unless otherwise shown in the drawings, welded joint design shall comply with MIL-STD-22.

20.5.3.2 Locations of welds, Welds critical to the achievement of shielding effectiveness of the HEMP protection subsystem are shown on the drawings.

20.5.3.3 Weld quality. The general quality of weldments shall be such that no gaps, burnthroughs, holes, cracks, bubbles, wornholes, undercuts, inclusions, or porosity shall be present. All shield welds shall be continuous (or circumferential or peripheral), and shall meet the acceptance standards of ANSI/AWS D1.1 and ANSI/AWS D1.3.

20.5.3.4 Weld defects. When inspection or testing indicates defects in the weld joints, the welds shall be repaired by the HEMP protection shielding contractor using a qualified welder. Defects shall be repaired in accordance with ANSI/AWS D1.1. Repaired welds shall be inspected and retested to the requirements for the original welds.

20.5.3.5 Welding safety. Safety precautions for welding shall conform to ANSI/AWS Z49.1.

20.5.4 Control of warping. Warping of the steel shield floor plates during and after installation shall be less than 3.2 mm (0.125 in) in 3.05 m (10 ft). Drive pins and anchor bolts, as indicated in the drawings, shall be employed to secure the floor plates to the concrete slab. The floor plates shall be inspected after being secured to the concrete and prior to welding under conditions of maximum design floor loading. If the plate deflection is greater than 1.6 mm (0.063 in) under the maximum applied load, additional drive pins or anchors shall be installed and the test shall be repeated. The steel floor plates shall be welded only after successful completion of the deflection load test.

20.5.5 Shield penetrations. All required shield penetrations shall be made only by the shielding contractor, who shall be held responsible for final HEMP protection subsys-

tern performance. The term "shield penetration" or "penetration" as used herein, specifically includes any fastener or supporting device passing through or attached to the shield material, as well as penetrations required for access and mechanical and electrical utilities. Any fasteners or supports for interior fixtures, conduits, or wire hangers (if penetrating the shield) shall be welded to the HEMP shield steel continuously around the periphery of each head to ensure freedom from electromagnetic field leaks.

20.5.6 Grounding and bonding.

20.5.6.1 Grounding. The drawings indicate the extent and general arrangement of the ground system. If any departures from the drawings are deemed necessary by the contractor, details of such departures and the reasons therefore shall be submitted as soon as practical to the Contracting Officer for approval. No such departures shall be made without the prior, written approval of the Contracting Officer. Grounding methods shall be in accordance with MIL-STD-188-125, MIL-STD-188-124, ANSI/NFPA 70, ANSI/NFPA 77, ANSI/NFPA 78, and ANSI/IEEE 142.

Materials used in connection with the installation of the ground system shall be approved for such systems by Underwriter's Laboratory. No combination of materials that forms an electrolytic couple of such a nature that corrosion from moisture is accelerated shall be used, unless moisture is permanently excluded from the junction of such metals. If a mechanical hazard is involved, the conductor size shall be increased to compensate, or suitable protection shall be provided. Suitable protection may be achieved by covering the connectors with molding or tubing made of wood, plastic, or other nonmetallic material.

Conductors shall be copper and of the grade ordinarily required for commercial electrical work, generally designated as 98 percent conductive when annealed. Copper conductors used for the ground system shall be bare conductors of the size indicated. Isolated internal grounds shall use insulated copper conductors as shown on the drawings.

Clamped connectors shall not be used for splicing conductors unless indicated for a specific purpose on the contract drawings.

20.5.6.2 Bonding. All facility metal that contacts the shield shall be bonded to the shield in accordance with MIL-STD-188-124, ANSI/IEEE C2, and MIL-B-5087, Class R, requirements. All bonds, inside and outside the HEMP protection subsystem, shall be tested for a maximum of 2.5 mΩ dc resistance between the metal-to-metal bonded surfaces, excluding the bond itself. All objects shall be bonded together with no intervening conductor, unless physical separation is absolutely necessary. Where straps are required, braided (not solid) straps shall be used.

20.5.7 Corrosion protection. All completed welds and the HEMP shield shall be protected from corrosion with coatings and other measures as required in the drawings.

20.6 Quality assurance.

20.6.1 General requirements. General quality assurance requirements for construction of the HEMP shield including requirements for test procedures and test reports, notifications of inspections and tests, Government witnesses, and remedial actions shall be in accordance with A.10.6.

20.6.2 Inspections and tests.

20.6.2.1 In-progress weld inspections and tests. All HEMP shield seam welds shall be inspected and tested for quality with visual, magnetic particle or dye penetrant, and SELDS methods. These in-progress inspections and tests shall also be performed on all primary shield welds used to install penetration protection under A.30 through A.60 and on welds for special protective measures when specified in A.70. Any shield weld determined to be defective shall be clearly marked and rewelded. All repaired welds shall be tested until there are no flaws. The contractor shall provide all equipment required for in-progress testing.

20.6.2.1.1 Visual inspection of welds. Visual inspection of welds shall be made after the welding is completed. All welds shall be visually inspected in accordance with ANSI/AWS D1.1.

20.6.2.1.2 SELDS testing. When large portions or sections of shield are in place, and before installing other accessories, attachments, and finishes, the welded seams shall be SELDS tested. Any leaks shall be repaired and retested. The leak-detection system shall use a 95- to 105-kHz oscillator and a hand-held receiver that is battery operated. The receiver or "sniffer" has a ferrite loop probe with the capability to sense leaks within 6.4 mm (0.25 in) of the probe location with a dynamic range of 140 dB. The source oscillator shall be used to drive the test section, with either loops placed behind the shield or with leads attached at opposite corners on the back side of the test section.

Test loops shall be placed under the shield floor prior to installation to assist in the detection of seam leaks in the floor. A loop shall be #16 AWG stranded, insulated copper wire, with a maximum 10 m (32.8 ft) diameter, or a maximum of 10 m per side for a square loop. Sides of a loop shall be at least 30 cm (1 f') in from the edge of the floor, with the leads or ends of the loop brought to an accessible location for attachment to the oscillator source. The loop wires shall be placed between the vapor barrier and the structural slab.

The contractor shall record the location of the permanent test leads and shall submit this information to the Contracting Officer for permanent reference.

20.6.2.1.3 Other in-progress testing for welds. All primary welds, conduit welds, and other welds in the HEMP shield shall be tested in accordance with ANSI/AWS D1.1 using magnetic particle inspection or dye penetrant inspection.

20.6.2.2 Complete (empty) shield effectiveness survey. The contractor shall perform measurements of the shielding effectiveness provided by the rf shield immediately after the shield has been completed, but before the interior finishes and duct work have been installed. All of the seams shall be swept with the seam leak detector (SELDS), and the entire shield shall be tested using plane wave shielding effectiveness tests per MIL-STD-188-125. All leaks, including leaks at penetrations such as shielded doors, piping and ventilation penetrations, and filter/ESA assembly installations, shall be identified, repaired, and retested.

The contractor shall provide the equipment required for testing in accordance with MIL-STD-188-125 and shall demonstrate, in the presence of the Contracting Officer's representative, that the completed HEMP protection subsystem provides the specified shielding effectiveness.

SELDS tests shall be performed as described in MIL-HDBK-423. Plane wave shielding effectiveness tests shall be performed in accordance with MIL-STD-188-125.

20.6.3 Acceptance testing. Acceptance testing of the HEMP shield shall be performed with the shielding effectiveness test in accordance with A.80.

30. SHIELDED DOORS AND ACCESS COVERS (See *handbook section* 9)

30.1 General requirements. Shielded doors and access covers shall be provided at all personnel entryways and equipment access ports through the HEMP electromagnetic barrier. The shielded doors and access panels shall have clear opening sizes, swings, and clearances indicated on the drawings. Materials and methods of construction not specifically detailed herein shall be in accordance with the practices of the established precision shielded-enclosure manufacturing industry, subject to the approval of the Contracting Officer.

The rf shielded doors and access panels are to be provided by a single supplier regularly engaged in the manufacture of these items. The assemblies shall be supplied complete with a rigid structural frame, hinges, latches, and all parts necessary for operation.

Shielded door assemblies will be subjected to repetitive use. Adequate structural strength and electromagnetic seals are required to meet the total specification, usage, and 15-year service-life requirements. Assemblies including doors, hardware, shield surfaces, seals, operating mechanisms, and other components shall function properly over this 15-year period with proper maintenance.

30.1.1 Scope. This part defines requirements for the performance, selection or construction, inspection, testing, and acceptance of rf shielded doors and access panels.

30.1.2 Performance requirements. Shielded doors and access panels shall provide shielding effectiveness in accordance with MIL-STD-188-125.

30.1.2.1 Warranty. The rf shielded doors and access panels shall be warranted to provide the required attenuation, when properly maintained, for a period of 15 years. The operating mechanisms, including interlocking components for the doors, shall be guaranteed by the contractor for one year or 50,000 cycles of opening and closing following the date of first beneficial use. Any part of these mechanisms failing during the guarantee period shall be replaced or repaired, including the required reinstallation and testing labor, by the contractor at no cost to the Government. Copies of the warranty shall be provided with each unit delivered.

30.1.3 Qualifications. All work shall be performed by a shielded door specialist and the required testing shall be performed or observed by a shielding quality assurance specialist. A shielded door specialist shall have successfully completed at least five similar shielded door projects of comparable size in the last 10 years. A shielding quality assurance specialist shall have performed the quality assurance program for at least five similar programs over the last 10 years. The Government reserves the right to approve the specialists, based on credentials provided in accordance with A.30.3.1.

30.2 Marking. Shielded doors and access covers shall have [HCI] tags, the manufacturer's nameplate, and operating instructions affixed on each side. Shielded doors and access covers shall also be stamped with a serial number.

The nameplate shall identify the manufacturer's name and model number for the assembly. The operating instructions for personnel doors shall provide procedures for normal use and for emergency exit. The operating instructions for equipment access covers shall include information such as lifting procedures, weight, bolt torquing requirements, and other information required for removal and reinstallation.

30.3 Submittals. The following submittals for shielded doors and access covers shall be provided to the Contracting Officer in accordance with A.10.7.

30.3.1 Door manufacturer credentials. Door supplier qualifications shall be submitted by the HEMP protection shielding contractor to the Contracting Officer for approval within 60 days after the notice to proceed. Adequate information shall be provided to show that the supplier is regularly engaged in the manufacture of rf shielded doors and access panels, and that doors of the design offered provide shielding effectiveness equal to or greater than the design requirements of MIL-STD-188-125.

30.3.2 Shop drawings. Shop drawings for shielded doors and access covers shall be submitted in accordance with A.10.7.2 and A.10.7.2.3. The shop drawings shall indicate complete details of construction and installation and shall include a complete parts list.

30.3.3 Certificates of compliance. Certification shall be provided attesting that rf shielded doors and access panels of the design to be supplied have been satisfactorily tested for compliance with this specification or higher specifications. Test data supporting these certifications shall also be provided.

30.3.4 Test plans and procedures. Detailed test plans and procedures for in-factory and other quality assurance testing of shielded doors and access covers shall be submitted in accordance with A.10.7.6.2. Test plans and procedures for frame welding quality assurance and acceptance testing shall be incorporated into the applicable HEMP shield test plans and procedures required by A.20.2.4. Test plans and procedures shall be submitted for approval at least 30 days before the planned date of conduct.

30.3.5 Test reports. Test reports for in-factory and other quality assurance testing of shielded doors and access covers shall be submitted within 15 days after completion of the test in accordance with A.10.7.7.2.

30.3.6 Operation and maintenance instruction manuals. Operation and maintenance instructions for shielded doors and access covers shall be included in the HEMP protection subsystem handbook and maintenance manual required by A.10.7.8 and A.10.7.9. Manuals should include, but not be limited to:

a. Hinge adjustment and maintenance

b. Normal periodic maintenance (such as cleaning of fingerstock)

c. Lubrication requirements

d. Lists of all replaceable parts with suggested sources

e. Instructions for replacing fingerstock

f. Requirements for periodic tests

g. Hardness maintenance and surveillance intervals

h. Maintenance/surveillance requirements for the interlock and alarm circuits and components

A parts list with parts location drawings shall be included. Wiring diagrams and schematics for door interlock and door alarms/indicators shall be included. Spare parts recommendations and cost quotations shall be provided for a one-year and fiveyear requirement.

30.4 Requirements.

30.4.1 Frames. The door and access panel frames shall be made of steel and shall be structurally rigid and suitable for welding to the surrounding structure and the shield. Each door and its frame shall be factory assembled as a unit, tested for proper operation as a unit, and shipped from the factory and installed as a unit. Care shall be used during packing and shipping to prevent any damage.

30.4.2 Hinged fingerstock doors.

30.4.2.1 Electromagnetic seal. Door electromagnetic seals shall be of the best design possible. Doors intended for exterior use shall be weatherproof and shall be protected to prevent moisture, wind, snow, or dirt from entering the building or from contacting the rf sealing surfaces, as required in MIL-STD-188-125. Door seals shall, after 50,000 openings and closings, continue to provide the shielding effectiveness specified in MIL-STD-188-125 and sealing components should not need to be replaced.

30.4.2.2 Latching mechanism. The rf shielded doors shall have a suitable three-point latching mechanism that shall provide proper compressive force for the rf fingerstock. The operating handle shall not mechanically interfere with the door frame when the shielded door is opened or closed. At no point in the operation should the force necessary to move the handle exceed 67 N (15 lb) on either side of the door. Force necessary to open the door shall not exceed 67 N (15 lb). Doors fitted with lever opening handles shall be designed so that a force of 1000 N (225 lb) may be applied at the free end in any direction without permanently deforming or damaging the operating mechanism. All emergency exits shall be supplied with “panic bar” exit devices.

30.4.2.3 Hinges. All doors shall be equipped with three, well-balanced, adjustable ball-bearing or adjustable, radial, thrust-bearing hinges suitable for equal weight distribution of the shielded doors. Hinges shall allow adjustment in two directions. A lubrication fitting at each hinge shall be provided, unless not required by the design of the hinge.

30.4.3 Sliding doors. All sliding doors shall be of the size and operating direction indicated. Clear openings indicated in the drawings shall not require dismantling of any part of the door. The doors shall be manually operable from either side, inside or outside, with a maximum pull of 133 N (30 lb), or power-assisted operation shall be provided. Door face panels and frames shall be constructed from reinforced steel, suitable for achieving the specified attenuation, and shall be not less than 10 gauge. Frames shall be constructed of steel shapes welded together to form a true rectangular opening. In the sealed position, the shielded doors shall provide at least the minimum attenuation specified in MIL-STD-188-125. The doors shall be designed for long life and reliability and shall not use rf gaskets, rf fingerstock, or sealing devices other than the specified direct metal-to-metal contact. A label shall be installed on the sliding doors warning against painting of the mating surfaces.

The doors shall slide on an easily-operated ball-bearing mechanism of proper strength for its use and purpose. Sealing pressure and controls shall operate on a compressed air system. The shielded door manufacturer shall provide the complete air system (including conservatively-rated compressor, tank, lines, filter and dryer and air control valves) required for long-term proper operation of the doors.

30.4.3.1 Door and frame assembly. All doors shall be provided as an assembly with a frame that will be welded into place in the primary shielding. The doors shall be accurately positioned in the frame.

30.4.3.2 Electromagnetic seal. The door and door periphery shall form a continuous seal by direct metal-to-metal contact. This continuous shield shall be implemented by the exertion of force from the pneumatic pressure system that shall maintain a nominal sealing pressure of 2.5 kg/cm^2 (35 lb/in^2) on the entire face of the independently hung panels, sealing each panel to the mating surfaces on the door frames. The door compartment shall be constructed in a manner such that each door panel forms an independent shield. Mating surfaces of the door and frame shall be factory prepared to provide a corrosion-resistant, conductive, long-life finish.

The finished area shall form a 9-cm (3.5-in) minimum peripheral margin on door panels and frames.

30.4.3.3 Sealing system. The pneumatic sealing system shall be actuated by a single, manual, air control valve, operable from inside or outside. The outside control panel shall also include a pressure regulator and filter. Normal operation of the air control valve shall unseal and allow manual operation of the door within 15 seconds. Each door shall have a separate control-valve system.

30.4.3.4 Power assist. Should the door mechanism preclude the manual operation of the door with a specified maximum pull of 133 N (30 lb), a power assist system shall be provided to meet the 133-N requirement. The power assist system shall include a pressure regulator and air control valve to control the speed and direction of the door, a pneumatic mechanism to provide power assist, an air control valve operable from inside or outside, and allowance for manual operation within 15 seconds should loss of air pressure occur. The power assist system shall be installed in such a manner that the clear opening of the door is not obstructed.

30.4.3.5 Servicing. The contractor shall provide a means of servicing the door mechanism without removing the door assembly and shall provide a removable panel for the complete removal of the door assembly.

30.4.4 Magnetically operated doors. Magnetically operated doors shall provide a clear opening with dimensions indicated in the drawings and shall open in the indicated direction. The doors shall be electrically operated and interlocked, with pushbutton controls activated from either side. The doors shall provide a minimum of 500,000 opening and closing cycles without need for major adjustments or repairs, when maintained in accordance with the manufacturer's instructions. In the latched and closed condition, the doors shall provide at least the minimum shielding effectiveness specified in A.30.1.2.

30.4.4.1 Frame and rails. The door frame shall be constructed of steel, of a type suitable for welding to the HEMP shield, and it shall be structurally rigid. The electromagnet rails shall be steel, with a thickness of at least 6.4 mm (0.25 in) and a channel depth of the dimensions required for installation of the coil. The rails shall be continuously welded to the frame.

30.4.4.2 Door leaf. The door leaf shall be fabricated using a single sheet of steel at least 1.3 mm (0.05 in) in thickness, and it shall be electrically bonded to the supporting structure. The door leaf shall overlap the electrical contact surface on the frame and rails by a minimum of 5 cm (2 in). The mating surface of the steel sheet shall be plated or otherwise prepared to provide a smooth, durable, and rust-resistant surface. The handle and hinges shall be mounted in a manner that does not penetrate the shield surface.

30.4.4.3 Hinges. The leaf shall mount to the frame by means of three adjustable hinges of sufficient strength to support the door leaf without warping or sagging. The hinges shall be mounted to the frame and leaf without penetrating the electromagnetic shielding surfaces.

30.4.4.4 Operation. The magnetically operated door shall go to an unlatched condition when the OPEN control is activated and the interlock is in an OPEN PERMISSIVE or OVERRIDE state. In the unlatched condition, the door shall open with a force no greater than 67 N (15 lb). The door shall be self-latching and self-closing when the leaf is moved within approximately 1 cm (0.4 in) of the frame.

The electromagnet and the control circuit shall be reliable and shall be provided with uninterruptible power. Upon complete loss of electrical power, the door shall fail in a closed condition. With the electromagnet deenergized, the door shall open with a force no greater than 133 N (30 lb).

30.4.5 Locks and interlocks for all doors.

30.4.5.1 Cypher locks. When specified by system design, cypher locks shall be supplied by the door manufacturer to assure compatibility of the electric bolt/strike and the controller. The cypher lock shall have the following features:

a. An exterior push-button panel with a minimum of 10 numbered buttons (a combination of four of these buttons in proper sequence will activate the door opener)

b. An adjustable time penalty to block efforts to activate the door opener if an incorrect or out-of-sequence button is pushed

c. An adjustable door-open time control

d. An easily changeable combination

e. A local alarm contact with manual reset to activate a bell if an incorrect or out-of-sequence button is pushed

f. A latch bolt to be electrically operated on low voltage directly from the door control unit

g. An adjustable volume bell to operate directly from the door alarm control unit

h. An adjustable volume buzzer to be activated by a separate push button and low-voltage ac source (with associated transformer and connections)

i. Battery backup power

30.4.5.2 Interlocks. Interlocks shall be provided for vestibule or tunnel door pairs. They shall be designed so that both doors cannot be opened at the same time during normal operation. An override shall be supplied to allow emergency egress, and an audible alarm shall be provided to indicate that both doors are open. The alarm will continue to sound as long as both doors are open. The contractor shall provide a low-voltage piezoelectric-type alarm, in a tamper-proof enclosure, in a location shown on the project drawings or as directed by the Government representative. The sound intensity shall be 45 dB (A) minimum at 3.05 m (10 ft). Lights shall be provided on one side of each door to indicate that the other door is open. Interlock systems can be integrated into the cypher lock system. The interlock system shall be powered by an uninterruptible power source and shall be in a fail-safe unlocked condition in the event of power failures.

30.4.5.3 Electric connectivity. Electric connectivity for sensors, alarms, and interlocks shall be installed in accordance with the door manufacturer's instructions, the approved drawings, and specification section: ELECTRICAL WORK, INTERIOR.

30.4.6 Threshold protectors. Threshold protectors shall be furnished for each of the rf shielded doors. They shall consist of portable ramps that protect the threshold when equipment carts or other wheeled vehicles are used to move articles across the threshold. The ramps may be asymmetrical to account for different floor elevations on each side, but the slope of the ramp shall not exceed 4:1 on either side. The ramps shall be designed to support a 227 kg (500 lb) force applied to a 7.6 cm x 1.3 cm (3 in x 0.5 in) footprint for a personnel door and a 907 kg (2000 lb) force applied to a 7.6 cm x 1.3 cm (3 in x 0.5 in) footprint for a cargo loading door. This footprint contact area is to be anywhere on the threshold seal area covered by the threshold protector. Mounting brackets, convenient to the entry, shall be provided to store the ramp when not in use.

30.4.7 Painting. Doors shall be factory prime painted with zinc (chromate) primer conforming to MIL-P-26915. Doors may be factory finish painted; however, the contractor must touch up any paint damaged during installation.

30.4.8 Spare parts, special tools, and supplies. The contractor shall furnish one full set of fingerstock for each hinged fingerstock door furnished under this contract. In addition, one set of manufacturer recommended spare parts for all doors of any style installed under this contract shall be provided. Shielded doors shall be designed to minimize

requirements for special tools. The contractor shall furnish any tools that are required to maintain the doors and that are not typically available from local tool vendors. The contractor shall provide any special lubricants or coatings required to maintain the doors, in sufficient quantities to last for six months.

30.5 Delivery and storage. Shielded doors and access panels shall be appropriately packaged for shipment. Packing containers shall provide physical and moisture protection, so that these items will be delivered to the job site in an undamaged condition. If special protection is required after installation, but before building completion, protection materials and protection instructions shall be provided by the door manufacturer.

30.6 Shielded door installation. Shielded door assemblies shall be installed as complete assemblies in preexisting prepared openings. Door assemblies shall be peripherally MIG welded to the shield in accordance with the manufacturer's installation instructions and approved shop drawings. Care shall be taken during installation to prevent damage, especially to fingerstock and rf gaskets. Doors, frames, thresholds, and associated hardware shall be furnished as preassembled matched units. Each unit shall be installed in its respective door opening in accordance with the door manufacturer's instructions. Alignment shall be maintained within the tolerances established by the door manufacturer. Alignment must be maintained during installation, tack welding, and final welding of the door assembly to preclude warpage.

30.6.1 Post-installation protection. During the construction phase, the opening and closing of doors shall be kept to a minimum, in order to limit the wear on the door and access panel components, particularly the contact surfaces. The contractor shall plan operations to keep the doors and panels in a permanently open position, with protection over sensitive components, during all construction activities. Temporary covers of not less than 16-mm (0.63-in) plywood shall be secured to protect exposed rf barrier contacts from physical damage. Easily removable masking or strippable coatings shall be applied over contact surfaces to eliminate soiling and corrosion. Coatings shall be removed and the contact surfaces cleaned with an appropriate solvent prior to final acceptance testing. Threshold protective ramps shall be in place when the doors are blocked open. All components that are damaged during the construction phase shall be replaced without cost to the Government.

30.7 Quality assurance.

30.7.1 General requirements. General quality assurance requirements for shielded doors and access covers including requirements for test procedures and test reports, noti-

fications of inspections and tests, Government witnesses, and remedial actions shall be in accordance with A.10.6.

30.7.2 Inspections. Quality assurance inspections shall be performed to assure that shielded doors and access covers are of high quality, professional workmanship, and in accordance with approved drawings and specifications. Inspections shall include:

a. Verification that dimensions and spacings are in accordance with the approved shop drawings and within allowable tolerances.

b. Inspection of the material, construction methods, and finishes.

Inspections shall be performed on 100 percent of the assemblies provided under this part.

30.7.3 Factory testing. Applicable tests described in A.30.7.3.1 through A.30.7.3.4 shall be performed on at least one shielded door of each type provided under this part and at least one shielded access cover of each type provided.

30.7.3.1 Swinging door statify load test. The swinging door shall be mounted and latched to its frame and then set in a horizontal position, so that the door opens downward and only the frame is rigidly and continuously supported from the bottom. With the door closed, a load of 195 kg/m^2 (40 lb/ft^2) shall be applied uniformly over the entire surface of the door for at least 10 minutes. The door will not be acceptable if this test causes any breakage, failure, or permanent deformation that results in the clearance between the door leaf and its frame to vary by more than 2 mm (0.08 in) from its original dimension.

30.7.3.2 Swinging door and hinged access cover sag test. The rf door and its frame shall be installed normally and opened 90 degrees. Two 45.4-kg (100-lb) weights, one on each side of the door or cover, shall be suspended from the door or cover within 12.5 cm (5 in) of the outer edge for at least 10 minutes. The door or cover will not be acceptable if this test causes any breakage, failure, or permanent deformation that results in the clearance between the door leaf or access cover and its frame to vary more than 2 mm (0.08 in) from its original dimension.

30.7.3.3 Power-operated door cycling test. The door shall be operated 2,500 complete open/close cycles. The door will not be acceptable if this test causes any extraordinary wear, breakage, failure, or permanent deformation.

30.7.3.4 Manually operated door handle pull test. The door shall be mounted and latched to its frame. A force of 1000 N (225 lb) shall be applied perpendicular (outward)

to the handle within 5 cm (2 in) of the end. The door will not be acceptable if this test causes any breakage, failure, or permanent deformation.

30.7.4 On-site tests. The following tests will be performed on-site after the doors and access panels are installed in the completed HEMP shield.

30.7.4.1 Shielding effectiveness test. Shielded doors and access panels will be tested for shielding effectiveness after installation in their normal operating location. The doors and panels shall comply with the minimum shielding effectiveness requirements of MIL-STD-188-125. Testing shall be performed in accordance with the requirements of MIL-STD-188-125.

30.7.4.2 Interlock configuration tests. The electrical and functional operation of the interlock system, including alarms and cypher locks (when included), shall be tested to verify performance.

30.7.5 Acceptance testing. Acceptance testing of all shielded doors and access covers shall be performed as part of the shielding effectiveness test in accordance with A.80.

40. WAVEGUIDE-BELOW-CUTOFF PROTECTION (See handbook section 10)

40.1 General requirements. Waveguide-below-cutoff (WBC) protection shall be provided for all piping, ventilation, and fiber optic cable penetrations of the HEMP electromagnetic barrier. WBC protection is also provided for microwave communications barrier penetrations, where shown in the drawings. WBCs and WBC assemblies may be shop-fabricated or commercially manufactured. WBC protection shall be fabricated and installed to meet all requirements of this part.

40.1.1 Scope. This part addresses the performance, fabrication, installation, and quality assurance requirements for waveguide-below-cutoff HEMP protective devices.

40.1.2 Performance requirements. Installed WBCs and WBC assemblies shall meet the shielding effectiveness requirements of MIL-STD-188-125.

40.1.2.1 Warranty. WBC protective devices shall be warranted by the manufacturer or contractor to provide the required shielding effectiveness for at least five years, when maintained in accordance with the supplied procedures.

40.1.3 Marking. All WBC Protective devices are hardness critical items and shall have [HCI] tags as shown in the drawings.

40.2 Submittals. The following submittals for WBC protective devices shall be provided to the Contracting Officer in accordance with A.1O.7.

40.2.1 Manufacturer's data. The contractor shall provide technical data for each type of commercially manufactured WBC protective device to be installed. The data shall include the manufacturer's credentials, catalog cuts, specifications, performance data, and outline drawings with dimensions, The submittal shall be of sufficient detail to show the manufacturer's ability to meet the requirements of this part. Data shall be submitted within 60 days after the notice to proceed, in accordance with A.10.7.l.

40.2.2 Shop drawings. Shop drawings for WBC protective devices shall be submitted in accordance with A.10.7.2 and A.10.7,2.4. Materials, dimensions, fabrication details, and installation methods for WBCs, WBC assemblies including frames, and weld plates where required shall be shown in the drawings.

40.2.3 Test plans and procedures. Detailed test plans and procedures for in-factory testing of commercially manufactured WBC protective devices shall be submitted in accordance with A. 10.7.6.2. Test plans and procedures for WBC weld quality assurance and acceptance testing shall be incorporated into the applicable HEMP shield test plans and procedures required by A.20.2.4. Test plans and procedures shall be submitted for approval at least 30 days before the planned date of conduct.

40.2.4 Test reports. Test reports for in-factory testing of commercially manufactured WBC protective devices shall be submitted within 15 days after completion of the test in accordance with A.10.7.7.2.

40.2.5 Operation and maintenance instruction manuals. Operation and maintenance instructions for WBC protective devices shall be included in the HEMP protection subsystem handbook and maintenance manual required by A.10.7.8 and A.10.7.9, respectively. Maintenance procedures shall include, but not be limited to, inspection methods and intervals, recommended frequency of replacement (if applicable), and instructions for repair and replacement.

40.3 Requirements.

40.3.1 Piping penetration protection. All piping penetrations of the HEMP barrier including utility piping, fire mains, vent pipes, and generator and boiler exhausts shall be made with piping WBC sections.

40.3.1.1 Material and dimensions. The material and size of each piping WBC section shall be as shown in the drawings. Unless otherwise specified, the material, wall thickness, and inside diameter shall conform to the following requirements:

a. The material shall be steel with a composition suitable for welding to the HEMP shield.

b. The minimum wall thickness shall be 3.2 mm (0.125 in).

c. The maximum inside diameter shall be 10 cm (4 in) or a metallic honeycomb insert with a maximum cell dimension of 10 cm shall be installed.

The piping WBC section shall have an unbroken length of at least five diameters (or at least five times the diagonal dimension of the cells) to form a WBC with a minimum cutoff frequency of 1.5 GHz.

40.3.1.2 Electromagnetic seal. The piping WBC section shall be circumferentially welded or brazed to the HEMP shield, to a pipe sleeve, or to a weld plate as shown in the drawings.

40.3.1.3 Pipe sleeve. When a pipe sleeve is required, it shall be constructed of steel with a composition appropriate for welding to the HEMP shield. The minimum wall thickness of the sleeve shall be 3.2 mm (0.125 in). The pipe sleeve shall be circumferentially welded to the HEMP shield or to a weld plate as shown in the drawings.

40.3.1.4 Weld plate. When a weld plate is required, it shall be constructed of the same steel as the HEMP shield (see A.20). The minimum weld plate thickness shall be 6.4 mm (0.25 in). The weld plate shall be circumferentially welded to the HEMP shield.

40.3.1.5 Exhausts. Generator and boiler exhausts shall be constructed as shown in the drawings and shall be configured as a WBC or WBC array with a minimum cutoff frequency of 1.5 GHz.

40.3.2 Ventilation penetration protection. All ventilation penetrations of the HEMP barrier shall be made with WBC arrays.

40.3.2.1 WBC array construction and dimensions. Each ventilation WBC array shall be a welded assembly or a commercially manufactured honeycomb panel as shown in the drawings. A welded WBC array shall be constructed from sheet metal or square tubes. The material shall be steel of a composition suitable for welding to the HEMP shield. Array cells shall be formed by welding the sheets at intersections or welding adjacent tubes along the entire length of the WBC section. The maximum cell size shall be 10 cm (4 in) on a side. The length of the WBC section shall be at least five times the diagonal dimension of the cells. The assembled array shall be hot-tin dipped in accordance with MIL-T-10727 for corrosion protection.

A commercially manufactured panel shall be made of small-cell brass honeycomb soldered into a steel frame. The thickness shall be at least five times the maximum honeycomb cell dimension.

40.3.2.2 Electromagnetic seal. The WBC array shall be circumferentially welded or brazed to a mounting frame.

40.3.2.3 Mounting frame. The mounting frame shall be constructed of the same steel as the HEMP shield (see A.20). The minimum frame thickness shall be 6.4 mm (0.25 in). The frame shall be circumferentially welded to the HEMP shield. The frame width shall be sufficient to ensure that the WBC array is not damaged when the frame is welded to the shield.

40.3.2.4 Pressure drop. Unless otherwise specified in the drawings, the pressure drop across the WBC array with all attachments in place shall not exceed 3.4 g/cm^2(0.1 in of water) at an air velocity of 305 m/min (1000 ft/min).

40.3.2.5 Attachments. Attachments to WBC array assemblies including weather shrouds, 'bird" screens, dampers, louvers, fans, and connections to ventilation ducts shall be provided as shown in the drawings. The methods of installation and configurations shall be carefully controlled to ensure that the shielding effectiveness performance is not degraded. No conductors such as wires and operating rods shall be permitted to pass through the WBC openings.

40.3.3 Fiber optic cable penetration protection. WBCs for fiber optic cable penetrations shall be provided as shown on the drawings. A fiber optic cable WBC shall meet the same requirements and shall be constructed and installed in the same manner as a piping WBC section. The WBC shall be capped or sealed to prevent air flow, as shown in the drawings.

40.3.4 Microwave communications penetration. The communications performance requirements and component selection criteria for microwave waveguides are stated in another section of the construction specifications. The waveguide shall be circumferentially bonded to the HEMP shield at the penetration, as shown in the drawings, for the purpose of HEMP protection.

40.4 Delivery and storage. WBC protective devices shall be appropriately packaged for protection during shipment and storage. Packaging shall provide physical and environmental protection to ensure that these items are delivered to the site in an undamaged condition. The packages shall be stored at the site under cover and shall be protected from extreme temperature changes and moisture that would cause damage. Defective units shall be replaced by the contractor at no cost to the Government. The HEMP protection shielding contractor shall be responsible for receiving and storing WBC protective devices at the job site.

40.5 Installation. Installation of WBCs and WBC assemblies shall be the responsibility of the HEMP protection shielding contractor. The WBC protective devices shall be installed at locations shown in the drawings. Installations shall be performed in accordance with manufacturer's recommendations, where applicable, and as shown in the approved shop drawings. Continuous circumferential welds around WBCs, pipe sleeves, weld plates, and frames as applicable shall be made to join the protective devices to the HEMP shield. All of the welds are primary shield welds, and they shall be made and inspected as required by A.20. If protection of WBC protective devices is required after installation and before building completion, protective measures shall be provided by the contractor.

40.6 Quality assurance.

40.6.1 General requirements. General qualify assurance requirements for WBC protective devices including requirements for test procedures and test reports, notifications of inspections and tests, Government witnesses, additional Government testing, and remedial actions shall be in accordance with A.10.6.

40.6.2 Inspections. Quality assurance inspections shall be performed to assure that WBCs and WBC assemblies are of high quality, professional workmanship, and in accordance with approved drawings and specifications. Inspections shall be performed on 100 percent of the WBC protective devices provided under this specification.

40.6.3 Factory testing of commercially manufactured WBC protective devices. At least one WBC protective device of each commercially manufactured type shall be factory tested to demonstrate compliance with the shielding effectiveness requirements. Testing

shall be performed in accordance with MIL-STD-188-125, appendix A, and the results shall be documented in a test report.

40.6.4 Acceptance testing. Acceptance testing of all WBC protective devices shall be performed as part of the shielding effectiveness acceptance test in accordance with A.80.

50. FILTER/ESA ASSEMBLIES (See handbook section 12)

50.1 General requirements. Filters and surge arresters shall be provided for all electrical conductors entering the HEMP electromagnetic barrier. These lines include, but are not limited to, power lines, signal lines, telephone lines, rf antenna lines, lines to dummy loads, alarm circuits, HVAC control, fire alarm, and lighting circuits. Complete filter/ESA assemblies shall meet all requirements defined in A.50 of this specification.

50.1.1 Scope. A.50 addresses the performance, construction, installation, and quality assurance test requirements for HEMP protection subsystem filter/ESA assemblies. It describes how the contractor shall:

a. Select filters and ESAs to meet attenuation and configuration requirements

b. Provide in-factory testing

c. Install filter/ESA assemblies

d. Provide quality assurance and acceptance testing

e. Provide data including manufacturer's data, drawings, certificates of compliance, test plans and reports, and operation and maintenance instructions

50.1.2 Performance requirements. The filter/ESA assemblies-incorporating the filters, the electronic surge arresters, and the enclosures specified herein-shall meet the transient suppression/attenuation requirements of MIL-STD-188-125. The presence of the protected electrical POE shall not degrade the shielding effectiveness of the HEMP shield.

50.1.2.1 Warranty. Filter elements shall be warranted by the manufacturer for a period of one year from acceptance by the Contracting Officer, or 18 months after installation, whichever is least. ESAs shall be warranted by the manufacturer for a period of three years after acceptance by the Contracting Officer, provided that surge life and other ratings are not exceeded. Filter/ESA enclosures shall be warranted to provide the shielding effectiveness required for a period of three years after acceptance by the Contracting Officer when maintained in accordance with the supplied procedures.

50.1.3 Standard products. In accordance with A.10.3.3, material and equipment shall be the latest standard products of a manufacturer regularly engaged in the manufacture of the filter/ESA assemblies or components described.

50.1.4 Standards compliance. Where equipment or materials are specified to conform to the standards of organizations such as Underwriters Laboratory (UL), the contractor shall submit proof of such conformance in accordance with A.10.3.4. The label and listing of the specified organization will be acceptable evidence. In lieu of the label or listing, the contractor shall submit a written certificate from an approved, nationally recognized testing organization that is adequately equipped and competent to perform such services. The certificate shall state that the items have been tested and that the units conform to the specified standard.

50.2 Submittals. The following submittals for filter/ESA assemblies shall be provialed to the Contracting Officer in accordance with A.10.7.

50.2.1 Manufacturer's data. Within 60 days after the notice to proceed, the contractor shall provide technical data for each type of filter and ESA described in this specification in accordance with A.10.7.1. The data shall include catalog cuts, specifications, performance data, and outline drawings with dimensions and shall be of sufficient detail to show the manufacturer's ability to meet the requirements of A. SO.

The following experience information shall also be provided on device manufacturers:

a. Statement of capabilities listing the number of employees, years in business, and volume of production.

b. List of five successful installations where filters and ESAs of comparable power rating and attenuation characteristics have been operating for at least one year without failure. The list shall include the site, quantity of filters, power rating, and attenuation requirements met. Names and telephone numbers of contacts that can verify satisfactory performance shall be provided.

50.2.2 Shop drawings. Filter/ESA assembly shop drawings shall be submitted in accordance with A.10.7.2 and A.10.7.2.5. Component outline drawings and methods of installation shall be shown.

50.2.3 Certificates of compliance. The manufacturer shall supply factory-certified test data that demonstrates the manufacturer's ability to meet the requirements, based on prior tests on similar filter assemblies. The data shall include the following:

a. Current overload capability

b. Insertion loss

c. Operating temperature range

d. Voltage drop

e. Dielectric withstanding voltage

f. Insulation resistance

g. Terminal strength

h. Calibration of test equipment used

50.2.4 Test plans and procedures. Detailed test plans and procedures for quality assurance and acceptance testing of filter/ESA assemblies shall be submitted in accordance with A.10.7.6. The test procedures shall be submitted for approval at least 30 days before the planned date of conduct. A clear definition of those tests that will be type tests and those tests that will be performed on all units shall be provided.

50.2.5 Test reports. Test reports for quality assurance and acceptance testing of filter/ESA assemblies shall be submitted in accordance with A.10.7.7.

50.2.6 Operation and maintenance instruction manuals. Operation and maintenance instructions for filter/ESA assemblies shall be included in the HEMP protection subsystem handbook and maintenance manual required by A.10.7.8 and A.10.7.9. The maintenance procedures shall include, but not be limited to, inspection methods and intervals, recommended frequency of replacement (if applicable), and instructions for replacing components.

50.3 Requirements.

50.3.1 Electrical filters. Filters specified herein are intended for use on power and signal lines to provide isolation from incoming HEMP transients. Required filters are shown on the design drawings and are listed in the filter/ESA Schedule, Drawing No. _____ Sheet _____. All filters shall be installed in enclosures on the outer surface of the HEMP electromagnetic barrier, mounted, and supported as shown on the design drawings and shop drawings. Installation locations shall be as indicated by the drawings. No filters shall be installed where they will be exposed to weather.

50.3.1.1 Filter construction. Individual filters shall be sealed in a steel case. The filter shall be sealed with an impregnating or potting compound meeting the requirements of MIL-F-15733 and having a flash point for operating temperature range B, as defined in table VIII of MIL-F-15733. After the filter is filled with an impregnating or encapsulating compound, the seams shall be welded or soldered. Hermetically sealed impregnated capacitors shall be used, or the complete filter assembly shall be vacuum impregnated. Individual filter cases shall be fabricated from not less than 2-mm (14-gauge) steel and finished with either a corrosion-resistant plating, or one coat of corrosion-resistant primer and two coats of finish enamel. When enamel finishes are used, the grounding surfaces shall be clean and free of paint or other nonconducting materials.

50.3.1.2 Filter mounting. Each filter unit shall be mounted individually in an enclosure containing one filter for each penetrating conductor, as specified. One end of the individual filter case shall be attached to the rf barrier plate between the two compartments to provide an rf-tight seal between the rf barrier plate and the filter case. The terminals of the filters shall project through openings in the rf barrier plate into the inner terminal compartment. The case of each filter shall be attached to both the enclosure and to the barrier plate to prevent undue stress being applied to the rf seal between the filter case and the rf barrier plate.

50.3.1.3 Filter replaceability. Filter units within the filter/ESA assembly enclosure shall be individually replaceable. Like filters shall be interchangeable.

50.3.1.4 Filter terminals. The filter terminals shall be ceramic-insulated standoff terminals with threaded studs. Unless otherwise specified in the Filter/ESA Schedule, filter terminals shall withstand the 89-N (20-lb) pull test when tested in accordance with A.50.6.3.1. For filters of rated current above 5 A, a separate standoff insulator or terminal block, connected by means of a suitably sized flexible lead to the ceramic filter terminal, shall be provided for electric connection to the filter. The standoff insulator terminals or insulated terminal blocks shall be mounted in the terminal compartments. Live parts shall be spaced in accordance with ANSI/NFPA 70. Filter leads shall be copper.

50.3.1.5 Bleeder resistor. All filters shall have external bleeder resistors to prevent electric shock from accidental discharge of filter capacitors while the power is disconnected. Drainage of stored charge shall be in accordance with ANSI/NFPA 70.

50.3.1.6 Marking of filters. Filters shall be marked inaccordance with general requirements of A.10.3.5. Each filter case shall be marked with [HCI] tags and with the

rated current, rated voltage, manufacturer's name, type of impregnating or potting compound, operating frequency, and model number. In addition, individual filter cases shall be durably marked by the manufacturer with the following:

> "WARNING: BEFORE WORKING ON FILTERS, TERMINALS MUST BE GROUNDED TO ENSURE DISCHARGE OF CAPACITORS."

Nameplates and warning labels shall be attached with epoxy.

50.3.1.7 Voltage rating. The voltage rating of each filter shall be as shown in the Filter/ESA Schedule.

50.3.1.8 Current rating. The full-load current rating of each filter shall be as shown in the Filter/ESA Schedule.

50.3.1.9 Operating frequency. The operating frequency shall be as shown in the Filter/ESA Schedule.

50.3.1.10 Passband impedance. Unless otherwise specified in the Filter/ESA Schedule, telephone filters shall have a nominal low-loss passband impedance of 600Ω.. Passband impedance requirements for other filters, if applicable, are stated in the Filter/ESA Schedule.

50.3.1.11 Insertion loss. Unless otherwise specified in the Filter/ESA Schedule, filters shall provide insertion loss of at least 100 dB from 14 kHz to 1 GHz when measured in accordance with A.50.6.3.2.

50.3.1.12 Voltage drop. Voltage drop at operating frequency shall not exceed two percent of the rated line voltage when the filter is fully loaded with a resistive load (unity power factor) and the voltage drop is measured in accordance with A.50.6.3.3.

50.3.1.13 Insulation resistance. The insulation resistance between each filter terminal and ground shall be greater than 1 MΩ when measured in accordance with A.50.6.3.4.

50.3.1.14 Dielectric withstanding voltage. Each filter shall be capable of operating continuously at full-rated voltage and withstanding an overvoltage test of 2.8 times the rated voltage for one minute when tested in accordance with A.50.6.3.5. In addition, each filter shall be capable of withstanding a 20-kV or 4-kA peak transient pulse of approximately 20 ns pulsewidth at full operating voltage, without damage.

50.3.1.15 Current overload capability. Filters shall be capable of operating at 140 percent of rated current for 15 minutes, 200 percent of rated current for one minute, and 500 percent of rated current for one second when tested in accordance with A.50.6.3.6. Short-term current capability shall be in excess of 10 times the rating without damage.

50.3.1.16 Reactive shunt current. Unless otherwise specified in the Filter/ESA Schedule, the reactive shunt current drawn by the filter operating at rated voltage shall not exceed 30 percent of the rated full-load current when measured in accordance with A.50.6.3.7.

50.3.1.17 Parallel filters. Where two or more filters are electrically tied in parallel, they shall equally share the load when measured in accordance with A.50.6.3.8.

50.3.1.18 Harmonic distortion. Total harmonics generated by the insertion of a filter shall not increase the line voltage distortion more than 2.5 percent when measured with a unity power factor in accordance with A.50.6.3.9.

50.3.1.19 Operating temperature range. Filters shall be designed for continuous operation at rated full-load current and operating voltage in an ambient temperature range of —25°C to +65°C. All components of the filter shall be suitable for continuous operation at rated full-load current at a temperature of 125°C without derating.

50.3.1.20 Temperature rise. Temperature rise shall not exceed 25 C“ when operating at rated full-load current and operating voltage, when measured in accordance with A.50.6.3.10.

50.3.1.21 Minimum life. Filters shall be designed for a minimum service life of 15 years.

50.3.2 Electronic surge arresters. ESAs specified herein are intended for use on power and signal lines to provide surge protection from incoming HEMP transients. Required ESAs are shown on the design drawings and are listed in the Filter/ESA Schedule, Drawing No. _____, Sheet____. All ESAs are to be installed in enclosures on the outer surface of the HEMP electromagnetic barrier, mounted, and supported as shown on the design drawings and shop drawings. Installation locations shall be as indicated by the drawings. No ESAs shall be installed where they will be exposed to the weather.

50.3.2.1 ESA construction. ESAs shall be metal oxide varistors (MOVs) or spark gaps as specified in the Filter/ESA Schedule. When a spark gap is specified, the case shall

be metal and the discharge shall be totally contained within the case. No external corona or arcing shall be permitted.

50.3.2.2 ESA mounting. ESAs shall be factory installed with minimum lead lengths within the outer compartment. For all filter/ESA assemblies except telephone filter/ESA assemblies, the ESAs shall be installed a minimum of 7.6 cm (3 in) apart, with terminals at least 7.6 cm (3 in) from a grounded surface. For telephone filter/ESA assemblies, the ESAs shall have a minimum clearance spacing of 2.5 cm (1 in), and terminals shall be at least 7.6 cm (3 in) from a grounded surface. Each phase, neutral, and telephone circuit conductor shall be connected through an ESA to the ground bus. The ESAs shall be located so that leads of minimum length connect the ESA ground terminal to the enclosure. Power line ESA wiring shall be #4 AWG (minimum). The gauge of the communication/signal line ESA wiring shall be the same or heavier than that used in the communication/signal line conductor. In all cases, total ESA lead length shall be less than 0.3 m (12 in).

50.3.2.3 ESA replaceability. ESA units within the filter/ESA assembly shall be individually replaceable. Like ESAs shall be interchangeable.

50.3.2.4 ESA terminals. Unless otherwise specified in the Filter/ESA Schedule, ESA terminals shall withstand the 89-N (20-lb) pull test when tested in accordance with A.50.6.3.1. Live parts shall be spaced in accordance with ANSI/NFPA 70. ESA leads shall be copper.

50.3.2.5 Marking of ESAs. ESAs shall be marked in accordance with general requirements of A.10.3.5. Individual ESAs shall be marked with [HCI] tags and with the manufacturer's name ox trademark and part number.

50.3.2.6 Voltage rating. The operating voltage rating of each ESA shall be as shown in the Filter/ESA Schedule.

50.3.2.7 Operating frequency. The operating frequency shall be as shown in the Filter/ESA Schedule.

50.3.2.8 Varistor voltage at 1 mA dc current and spark gap dc breakdown voltage. The varistor voltage at 1 mA dc current or the spark gap dc breakdown voltage shall be in the range specified in the Filter/ESA Schedule, when measured in accordance with A.50.6.3.11.

50.3.2.9 ESA impulse sparkover voltage. Unless otherwise specified in the Filter/ ESA Schedule, impulse sparkover voltage of the ESAs shall be less than 4000 V on a voltage

surge of either polarity, having a rate of rise of 1000 V/ns, when measured in accordance with A.50.6.3.12.

50.3.2.10 ESA clamping voltage. Unless otherwise specified in the Filter/ESA Schedule, clamping voltage of the ESAs shall be less than 900 V at a current of 10 kA when tested in accordance with A.50.6.3.13.

50.3.2.11 ESA extinguishing characteristics. Unless otherwise specified in the Filter/ESA Schedule, the ESAs shall extinguish and shall be self-restoring to the normal nonconductive state within one-half cycle at the operating frequency, when tested in accordance with A.50.6.3.14.

50.3.2.12 Extreme duty discharge capability. The extreme duty discharge capability is the peak current level of a single 8 x 20 μs pulse that the ESA must survive (the pulse has a 10-90 percent rise time of 8 μs and fall time to a value of 36.8 percent of the peak in 20 μs).

ESAs for commercial power lines shall have an extreme duty discharge capability equal to or greater than 70 kA, when measured in accordance with A.50.6.3.15.

ESAs for power feeders to loads such as area lighting and external HVAC equipment, shall have an extreme duty discharge capability equal to or greater than 50 kA.

ESAs for control circuits such as interior alarms, indicator lights, door access controllers, HVAC controls, and telephones, shall have an extreme duty discharge capability equal to or greater than 10 kA.

50.3.2.13 Operating temperature range. ESAs shall be designed for continuous operation at rated voltage in an ambient temperature range (inside the filter/ESA enclosure) of –25°C to +125°C.

50.3.2.14 Minimum operating life. The ESAs shall have the capability to conduct 2000 pulses with a peak amplitude of 4 kA and a 50 ns x 500 ns waveshape before failure. Life testing, when required, shall be in accordance with A.50.6.3.16.

50.3.3 Filter/ESA enclosures.

50.3.3.1 Enclosure construction. The assembly enclosure shall be made of steel, not less than 2.7 mm (12 gauge) in thickness, with welded seams. The enclosures shall be galvanized 01 electroplated after fabrication and welding, or the enclosures shall be finished

with a corrosion inhibiting primer and two coats of finish enamel of the manufacturer's standard color. Terminal boards and surge arresters shall be mounted on an interior subpanel, so that no mounting hardware penetrates the enclosure. Lifting eyes and the ground bus shall be circumferentially welded to the enclosure structure.

50.3.3.2 Enclosure configuration. The imbedded configuration shall be used for all filter/ESA assemblies, as required by MIL-STD-188-125. The enclosures shall have two compartments. Each compartment shall be large enough to allow for the connection of the number and size conductors to be used and for the installation and removal of ESAs and filter elements. The space provided shall satisfy the requirements of ANSI/NFPA 70 for spacing between live parts. The input terminal compartment shall be separated from the output terminal compartment by a solid steel barrier plate of at least the same thickness as the enclosure. The barrier plate shall extend across the entire width of the enclosure and shall be peripherally welded to the HEMP shield.

Unless otherwise specified in the Filter/ESA Schedule, the compartments, are not required to be rf-tight. Shielded compartments, when required as a special protective measure, shall comply with A.70.

50.3.3.3 Access openings and cover plates. Access openings shall be large enough for easy access to filter terminals and surge arresters and for easy removal and replacement of filter elements. Cover plates for imbedded filters shall generally provide mechanical protection only. Captive nuts shall be used. Access cover plates shall be of the type shown in the drawings and constructed of steel not less than 2.7 mm (12 gauge). The finish shall be the same as specified for the enclosure. Covers shall be attached, so they may be easily removed and replaced, and shall be fitted with 15.2-cm (6-in) handles.

50.3.3.4 Conduit connections. The terminal compartments shall have no knockouts. Each compartment shall be large enough to allow conduit nipples to be tack welded or seam welded in place and be sized and located as required by the job-site conditions.

50.3.3.5 Ground bus. A copper ground bus, 6.4 cm (0.25 in) in thickness, 3.2 cm (1.25 in) in width, and having the required length, shall be installed on the interior of both compartments. A threaded stud shall be provided for each ESA ground conductor. The ground bus and studs shall have no paint and shall be coated with lightweight machine oil.

50.3.3.6 Enclosure mounting. Filter/ESA enclosures shall be installed on stands or supports so that the weight of the assembly is not transferred to the HEMP shield.

50.3.3.7 Marking of enclosures. Each enclosure shall have an [HCI] tag and a manufacturer's nameplate affixed on each cover. The nameplate shall state the filter rated current, rated voltage, operating voltage, and operating frequency; the number of phases, lines or pairs; the manufacturer's name; the total filter unit weight; the part designator number; and the model number. The nameplate shall be mounted on the filter enclosure to be visible after installation, without removing cover plates or disturbing the interior parts or wiring.

50.3.4 Filter/ESA assemblies.

50.3.4.1 Insertion loss. When assembled and installed, the filter/ESA assembly shall provide at least the minimum insertion loss specified for the filters, when measured in accordance with A.50.6.3.17.

50.3.4.2 Insulation resistance. When assembled and installed, insulation resistance of the filter/ESA assembly shall be at least the minimum applicable value for the filters, when measured in accordance with A.50.6.3.18.

50.3.4.3 Dielectric withstanding voltage. When assembled and installed, except that the ESAs shall be disconnected, the filter/ESA assembly shall withstand twice the rated operating voltage of the filters for a period of one minute, without degradation or damage, when tested in accordance with A.50.6.3.19.

50.3.4.4 Operating temperature. The filter/ESA assembly shall be rated for continuous operation, with all filters at rated voltage and full-load currents, in ambient temperatures from –25°C to +65°C (measured outside the rf filter cabinet).

50.3.4.5 Temperature rise. When assembled and installed, the temperature rise of the hottest component in the filter/ESA assembly, with all filters operating at rated voltage and full-load currents, shall not exceed 40 C°, when measured in accordance with A.50.6.3.20.

50.3.4.6 Pulsed current injection testing. When installed and operational, the filter/ESA assembly shall provide the transient suppression/attenuation required by MIL-STD-188-125. Acceptance testing shall be performed as required by A.50.6 and A.80.

50.3.4.7 Shielding effectiveness. When the filter/ESA is installed and operational, the electromagnetic barrier in the area of the installation shall satisfy the shielding effectiveness requirements of MIL-STD-188-125. Acceptance testing shall be performed as required by A.50.6 and A.80.

50.4 Delivery and storage. All filter/ESA assemblies shall be completely protected from weather, dust, and incidental contact during shipment and storage. Power filter/ ESA assemblies shall be bolted on oak pallets, using the mounting brackets, and shall be protected with 2.5-cm (l-in) dimension lumber on all four surfaces. Each filter/ESA assembly shall be sealed with a minimum of 0.2-mm (0.008 in) plastic wrap, and shipped with desiccant in the shipping containers. All filter/ESA assemblies shall be delivered to the job site in an undamaged condition. Two spray cans of exterior paint (to match filter/ESA assemblies) shall be shipped with the assemblies for job site touch-up. The HEMP protection subsystem contractor shall be responsible for receiving and storing the filter/ESA assemblies at the job site.

50.5 Installation. Installation of the filter/ESA assembly shall be the responsibility of the HEMP protection shielding contractor. The work may be subcontracted to the filter/ESA supplier. The installation shall be in accordance with the manufacturer's recommendations and as shown in the shop drawings.

50.6 Quality assurance.

50.6.1 General requirements. General quality assurance requirements for filter/ ESA assemblies-including requirements for test procedures and test reports, notifications of inspections and tests, Government witnesses, additional Government testing, and remedial actions-shall be in accordance with A.10.6.

50.6.2 Inspection and test requirements.

50.6.2.1 Filters.

50.6.2.1.1 Inspection. Factory quality control procedures shall be performed to assure that filter assemblies are of high quality and workmanship and are in accordance with approved drawings, specifications, and testing procedures. The contractor shall provide adequate documentation to prove acceptability. Inspections shall be conducted on 100 percent of all filters to be provided under this specification, to verify compliance with the requirements of A.50.1.3 and A.50.1.4.

50.6.2.1.2 Factory testing of all filters. All units to be delivered under this specification shall be 100-percent tested to the following requirements:

a. Insertion loss (A.50.3.1.11)

b. Insulation resistance (A.50.3.1.13)

c. Harmonic distortion (A.50.3.1.18)

Factory testing may be witnessed by the Government at its option. The Contracting Officer shall be notified at least 14 days before the completed filters are ready for factory testing and may provide one or more Government representatives to witness and sign off the factory tests. Filter assemblies shall not be shipped from the factory until approval is given by the Contracting Officer.

50.6.2.1.3 Filter type testing. The manufacturer shall provide test data and certification that at least one filter of each type provided has been tested and conforms to the requirements of A.50.3.1.

50.6.2.2 ESAs.

50.6.2.2.1 ESA inspections. Factory quality control procedures shall be performed to assure that ESAs are of high quality and workmanship and are in accordance with approved drawings, specifications, and testing procedures. The contractor shall provide adequate documentation to prove acceptability. Inspections shall be performed on 100 percent of all ESAs to be provided under this specification, to verify compliance with A.50.1.3 and A.50.1.4.

50.6.2.2.2 ESA type testing. The manufacturer shall provide test data and certification that one ESA of each type provided has been tested and conforms to the requirements of A.50.3.2.

50.6.2.3 Enclosures. Enclosures shall be factory inspected to ensure that they are of high quality and workmanship and are in accordance with the approved drawings and specifications.

50.6.2.4 Filter/ESA assemblies. The manufacturer shall provide test data and certification that at least one filter/ESA assembly has been tested and conforms to the requirements of A.50.3.4.1 and A.50.3.4.2. Additionally, at least one filter/ESA assembly of each type rated for operating currents of 200 A or greater shall be tested to demonstrate compliance with A.50.3.4.5.

50.6.3 Test methods.

50.6.3.1 Terminal strength test (filters and ESAs). Filter and ESA terminal strength tests, when required, shall be performed in accordance with MIL-STD-202, Method 211A, Test Condition A, modified as follows:

a. Testing shall be performed with the components mounted in the filter/ESA assembly enclosure or mounted on a plate by the same holding method that will be used for mounting in the enclosure.

b. The applied force shall be 89 N (20 lb) unless otherwise specified. The applied force shall not be limited to values listed in MIL-STD-202.

50.6.3.2 Filter insertion loss measurements.

50.6.3.2.1 Power filters. Power filter insertion loss measurements, when required, shall be performed in accordance with MIL-STD-220, modified as follows:

a. The filters shall be installed in the filter/ESA assembly enclosure.

b. The load current power supply shall operate at the rated voltage of the filters and shall be capable of providing any current from no-load through rated full-load current.

c. The rf signal generator shall be a swept continuous wave (CW) source. The buffer networks shall be modified to permit valid measurements over the entire frequency band on which insertion loss requirements are specified (14 kHz-1 GHz).

d. The receiver or network analyzer shall be capable of operating over the entire frequency band on which insertion loss requirements are specified (14 kHz-1 GHz). Sensitivity shall be adequate to provide a measurement dynamic range at least 10 dB greater than the insertion loss requirement.

e. The load impedances shall be resistive and shall be capable of dissipating the rated full-load filter current.

f. Insertion loss measurements shall be made at 20 percent, 50 percent, and 100 percent of the filter full-load operating current.

50.6.3.2.2 Communication/signal line filters. Insertion loss measurements on communication/signal line filters shall be performed as described in A.50.6.3.2.1 of this specification, except that insertion loss measurements are required at a load impedance equal to the image impedance of the filter.

50.6.3.3 Filter voltage drop/de resistance measurements. voltage drop masurements on ac filters, when required, shall be performed in accordance with MIL-F-15733, except that testing shall be performed with the components mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

Voltage drop measurements on dc filters, when required, shall be performed in accordance with MIL-F-15733, except that testing shall be performed with the components mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

50.6.3.4 Filter insulation resistance measurements. Filter insulation resistance measurements, when required, shall be performed in accordance with MIL-STD-202, Method 302, modified as follows:

a. Testing shall be performed with the filters mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure. The bleeder resistor shall be disconnected.

b. The test shall be conducted at the largest test condition voltage (100 V, 500 V, or 1000 V) that does not exceed the rated peak ac voltage or the rated dc voltage.

c. A separate dc power supply may be used to charge the filters to the test voltage.

d. The insulation resistance value shall be read with a megohmmeter and recorded after the reading has stabilized (rather than at a specified time).

50.6.3.5 Filter dielectric withstanding voltage test. Filter dielectric withstanding voltage tests, when required, shall be performed in accordance with MIL-STD-202, Method 301, modified as follows:

a. Testing shall be performed with the components mounted in the filter/ESA assembly enclosure.

b. Filters for ac circuits shall be tested with an ac source.

c. Filters for dc circuits shall be tested with a dc source.

d. In addition to the physical examination, insulation resistance measurements shall be made (or repeated) after the dielectric withstanding voltage test.

50.6.3.6 Filter current overload test. Filter current overload tests, when required, shall be performed in accordance with MIL-F-15733, except that testing shall be performed with the filters mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

50.6.3.7 Filter reactive shunt current measurement. Filter reactive shunt current measurements, when required, shall be performed in accordance with the following procedure:

a. Testing shall be performed with the filters mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

b. The filter shall be terminated in the inner compartment in an open circuit.

c. Rated ac voltage shall be applied between the filter outer compartment terminal and the enclosure (or metal plate).

d. The ac current into the outer compartment terminal shall be monitored. This current is equal to the filter reactive shunt current.

50.6.3.8 Power filter current sharing measurements. Current sharing measurements between parallel filters, when required, shall be performed in accordance with the following procedures:

a. Testing shall be performed with the filters mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

b. The filter inner compartment terminals shall be loaded with a resistor equal in value to the rated operating voltage divided by the sum of the current ratings of the devices in parallel. The resistor shall be capable of dissipating the total current.

c. Rated operating voltage shall be applied at the filter outer compartment terminals.

d. The current into each filter outer compartment terminal shall be monitored. Filters are considered to share the load equally when all measured currents are within five percent of the average current per filter.

50.6.3.9 Filter harmonic distortion measurements. Harmonic distortion measurements, when required, shall be made using a spectrum analyzer having a dynamic range of 70 dB or greater and a frequency range from 10 Hz to 1.7 GHz or greater. Total harmonic

distortion shall be measured at the input and output terminals of the filter when operating at 25, 50, and 100 percent of rated full-load current.

50.6.3.10 Filter temperature rise measurements. Filter temperature rise measure ments, when required, shall be performed in accordance with MIL-F-15733, modified as follows:

a. Testing shall be performed with the filters mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

b. The period during which the filter is at rated voltage and full-load current shall be until temperature equilibrium is reached or 24 hours, whichever is longest.

50.6.3.11 Varistor voltage at 1 mA dc current and spark gap dc breakdown voltage measurements. Measurements of metal oxide varistor (MOV) voltage at 1 mA dc current and spark gap dc breakdown voltage, when required, shall be made in accordance with the following procedure:

a. Testing shall be performed with the ESAs mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method which will be used for mounting in the enclosure.

b. A variable dc power supply shall be connected between the ESA terminal and the enclosure (or plate).

c. The applied voltage shall be increased at a rate not to exceed 10 percent of the rated firing voltage per second.

d. The varistor voltage at 1 mA dc current is the power supply output voltage, when the output current is 1 mA. The spark gap dc breakdown voltage is the applied voltage just prior to breakdown (indicated by a rapid decrease in the voltage across the device). Reenergize the power supply immediately after the value has been recorded.

50.6.3.12 ESA impulse sparkover voltage measurement. ESA impulse sparkover voltage measurements, when required, shall be performed in accordance with the following procedures:

a. Testing shall be performed with the spark gaps mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method which will be used for mounting in the enclosure.

b. The pulse generator shall be connected between the spark gap terminal and the enclosure (or plate) with a minimum inductance connection. The pulse generator shall be capable of providing a ramp voltage of 1 kV/ns to a peak voltage which is at least twice the expected impulse sparkover voltage (into an open-circuit load).

c. Voltage across the spark gap shall be monitored on an oscilloscope or transient digitizing recorder, capable of at least 1-ns resolution. The peak transient voltage during the pulse is the impulse sparkover voltage.

50.6.3.13 ESA clamping voltage measurement. ESA clamping voltage measurements, when required, shall be performed in accordance with the following procedures:

a. Testing shall be performed with the ESAs mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method which will be used for mounting in the enclosure.

b. The pulse generator shall be connected between the ESA terminal and the enclosure (or Plate) with a minimum inductance connection. The pulse generator shall be capable of providing a 10-kA current pulse, on an 8 µs x 20 µs waveshape, into the ESA.

c. Current through the ESA and voltage across the ESA shall be monitored on oscilloscopes or transient digitizing recorders. The asymptotic voltage during the 10-kA portion of the pulse is the clamping voltage.

50.6.3.14 ESA extinguishing test. ESA extinguishing tests, when required, shall be performed in accordance with the following procedures:

a. Testing shall be performed with the ESA mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method which will be used for mounting in the enclosure.

b. An ac power source at the rated operating voltage and frequency, capable of providing at least 25 A into a short-circuit load, shall be connected between the ESA terminal and the enclosure (or plate). A pulse generator, capable of providing a short pulse which will fire the ESA (amplitude and waveshape are not critical), shall also be connected across the ESA.

c. Voltage across the ESA shall be monitored on an oscilloscope or transient digitizing recorder. A series of ten pulses shall be injected. Performance of the ESA is satisfactory if the arc extinguishes (indicated by reoccurrence of the sinusoidal voltage waveform) within 8.5 ms after the start of each pulse.

50.6.3.15 ESA extreme duty discharge measurements. ESA extreme duty discharge current measurements, when required, shall be performed in accordance with the following procedures:

a. Testing shall be performed with the ESAs mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

b. The pulse generator shall be connected between the ESA terminal and the enclosure (or plate) with a minimum inductance connection. The pulse generator shall be capable of supplying a current pulse of the prescribed amplitude, on an 8 x 20 μs waveshape, to the ESA.

c. Only a single pulse is required. Current through the ESA and voltage across the ESA shall be monitored on oscilloscopes or transient digitizing recorders. The ESA shall be visually monitored during the pulse for indications of external breakdown.

d. After the pulse, the ESA shall be carefully inspected for charring, cracks, or other signs of degradation or damage. The ESA dc breakdown voltage test shall be performed (or repeated) after the extreme duty discharge test.

50.6.3.16 ESA minimum operating life test. ESA operating life tests, when required, shall be performed in accordance with the following procedures:

a. Testing shall be performed with the ESAs mounted in the filter/ESA assembly enclosure or mounted on a metal plate by the same holding method that will be used for mounting in the enclosure.

b. The pulse generator shall be connected between the ESA terminal and the enclosure (or plate) with a minimum induction connection. The pulse generator shall be capable of supplying repetitive 4 kA current pulses, with a 50 ns x 500 ns Waveshape, to the ESA.

c. A series of ten pulses is required. Current through the ESA and voltage across the ESA shall be monitored on oscilloscopes or transient digitizing recorders. The ESA shall be visually monitored during the series of pulses for indications of external breakdown.

d. After the series of pulses, the ESA shall be carefully inspected for charring, cracks, or other signs of degradation or damage. The ESA dc breakdown voltage test shall be performed (or repeated) after the surge life test.

50.6.3.17 Filter/ESA assembly insertion loss measurements. Filter/ESA assembly insertion loss measurements, when required, shall be performed as described in A.50.6.3.2 of this specification, except that the filter/ESA assembly shall be complete and installed (except for connections to the external and internal circuits). Measurements shall be made on each conductor that penetrates the shield through the assembly.

50.6.3.18 Filter/ESA assembly insulation resistance measurements. Filter/ESA assembly insulation resistance measurements, when required, shall be performed as described in A.50.6.3.4 of this specification, except that the assembly shall be complete and installed (except for connections to the external and internal circuits). Measurements shall be made on each conductor that penetrates the shield through the assembly.

50.6.3.19 Filter/ESA dielectric withstanding voltage test. Filter/ESA assembly dielectric withstanding voltage tests, when required, shall be performed as described in A.50.6.3.5, except that when spark gap surge arresters with a dc breakdown voltage less than twice the rated operating voltage are used, the test voltage shall be 90 percent of the dc breakdown voltage. Measurements shall be made on each conductor that penetrates the shield through the assembly. ,

50.6.3.20 Filter/ESA assembly thermal measurements. Filter/ESA assembly thermal measurements, when required, shall be performed in accordance with the following procedures:

a. The filter/ESA assembly shall be complete and installed.

b. The assembly inner compartment terminals shall be terminated in resistive loads. The value of the resistors shall be rated voltage divided by rated current. The load shall be capable of operating continuously at rated voltage, frequency, and current.

c. Thermocouples shall be placed at selected locations on components and surfaces within the filter/ESA enclosure. All expected 'hot spots" shall be monitored.

d. Sources operating at the rated voltage and frequency and capable of supplying full-load current shall be connected at the assembly outer compartment terminals. All conductors that penetrate the shield through the assembly shall be simultaneously energized during this test.

e. All access covers shall be secured.

f. The duration of the test shall be until temperature equilibrium is reached or 24 hours, whichever is greater. Temperature equilibrium exists when the temperature differential (monitored temperature minus ambient temperature) at the hottest spot and

the average temperature differential for all monitored points remain constant within -0.2 C" for a period of two hours.

g. Voltages and currents on all conductors and temperatures at monitored points shall be recorded at 15-minute intervals during the first six hours and at 30-minute intervals thereafter.

60. SHIELDED CONDUITS AND PULL BOXES *(See handbook section 12)*

60.1 General requirements. Shielded conduits and pull boxes shall be provided for HEMP protection of cable runs between two electromagnetic barriers and for other applications as shown in the drawings. Conduits and pull boxes shall be interior or exterior, and exterior conduits and pull boxes shall be aboveground or buried as shown in the drawings. This part addresses fabrication and installation of shielded conduits and pull boxes.

60.1.1 Marking. Shielded conduits and pull boxes are hardness critical items and shall have [HCI] tags as shown in the drawings.

60.2 Requirements.

60.2.1 Material and dimensions. Shielded conduits and pull boxes shall be constructed of steel with a composition suitable for welding to the HEMP shield. The diameter of each conduit and the dimensions of each pull box shall be as shown in the drawings. The minimum wall thickness of the conduit shall be 3.2 mm (0.125 in). The minimum thickness of plate used to construct the pull box shall be 6.4 mm (0.25 in).

60.2.2 Shielded conduit. Shielded conduit shall be rigid steel pipe with threaded and circumferentially welded joints. Before assembly, all parts shall be wire-brushed to ensure that they are free from dirt and rust. Conduits and the coupling shall be threaded together and torqued to values shown in the drawings. After assembly, the coupling shall be circumferentially welded to each conduit. The welds shall be painted with zinc-rich paint.

60.2.3 Shielded pull boxes. Shielded pull boxes shall be constructed from steel plate and shall have continuously welded seams. The pull box access cover shall be welded in place or rf gasketed and bolted as shown in the drawings. Holes for conduits shall be predrilled. The bottom of the box shall be sloped, and one hole at the low point shall be drilled and tapped to accept a 6.4 mm (0.25 in) by 5.1 cm (2 in) long pipe nipple to act

as a WBC vent and condensate drain. The nipple shall be circumferentially welded to the pull box.

Before assembly, conduits and the conduit entry on the pull box shall be wire-brushed to ensure that they are free of dirt and rust. Conduits shall be circumferentially welded to the pull box. The welds shall be painted with a zinc-rich paint.

60.2.4 Corrosion protection. Shielded conduits and pull boxes shall be protected from corrosion as required in specification section: ELECTRICAL WORK, INTERIOR or section: ELECTRICAL WORK, EXTERIOR, as applicable.

60.3 Installation. Shielded conduits shall be circumferentially welded to the HEMP shield at the locations shown in the drawings. These welds shall be the responsibility of the HEMP protection shielding contractor.

60.4 Quality assurance.

60.4.1 Inspections and tests. Circumferential welds at shielded conduit joints and entries into pull boxes and the HEMP shield and seam welds used to construct shielded pull boxes are primary shield welds. They shall be made and inspected as required by A.20. Shielding effectiveness tests of pull boxes and enclosures, when required, shall be performed in accordance with MIL-STD-188-125 or in accordance with a contractor-prepared, Government-approved test plan.

60.4.2 Acceptance testing. Acceptance testing of shielded conduits and pull boxes shall be performed as part of the pulsed current injection test in accordance with A.80.

70. SPECIAL PROTECTIVE MEASURES FOR CONDENSING UNITS (See handbook section 14)

70.1 General requirements. Special protective measures (SPMs) for HEMP hardening the condensing units shall be provided as shown in the drawings. SPMs shall include a system of shielded conduits, pull boxes, and enclosures containing power and control wiring and circuit components, filter/ESAs on electrical conductors, and surge arresters on motor and sensor leads. This part addresses the performance, fabrication, installation, and quality assurance requirements for SPMs provided for protection of the condensing units.

70.1.1 Marking. The shielded conduits, pull boxes, and enclosures are hardness critical items and shall be marked with ['] tags as shown in the drawings. Filter/ESA assemblies shall be marked in accordance with A.50.

70.2 Requirements.

70.2.1 Shielded conduits, pull boxes, and enclosures. Shielded conduits provided under this part shall meet the requirements of A.60 for shielded conduits. Shielded pull boxes and enclosures provided under this part shall meet the requirements of A.60 for shielded pull boxes. No controls or indicators shall be installed on the shielded enclosures.

70.2.2 Filter/ESA assemblies. Filter/ESA assemblies provided under this part shall meet the requirements of A.50, except that the imbedded enclosure configuration is not required.

70.2.3 Motor and sensor protection. The condensing unit motors shall be totally enclosed fan-cooled motors with metal cases. MOVs shall be installed in the connection boxes on the motors and sump temperature sensors. The MOVs on three-phase motors shall be installed phase-to-phase. MOVs on single-phase motors and temperature sensors shall be installed between the two electrical conductors. The varistor voltages at 1 mA dc current and extreme-duty discharge currents shall be as shown in the drawings.

70.3 Installation. Conduits provided under this part shall be circumferentially welded at all couplings and entries into shielded pull boxes and enclosures. These welds shall be the responsibility of the HEMP protection shielding contractor. Mountings and supports shall be provided as shown in the drawings. Mounting bolts shall not penetrate the shielded topology.

70.3.1 Inspections and tests. Circumferential welds at shielded conduit joints and entries into pull boxes and shielded enclosures and seam welds used to construct shielded pull boxes and enclosures shall be made and inspected as required for primary shield welds by A.20.

70.3.2 Acceptance testing. Acceptance testing of special protective measures for the condensing units shall be performed in accordance with A.80.

80. HEMP PROTECTION SUBSYSTEM ACCEPTANCE TESTING (See handbook section 16)

80.1 General requirements. The HEMP protection subsystem acceptance test shall be conducted after construction is complete, all penetrating installations have been completed, specifically including all lighting and utilities, and all finishes have been applied.

The contractor shall furnish the services of an independent testing agency or consultant, approved by the Contracting Officer, to test the HEMP protection subsystem. The contractor shall verify that the agency or consultant is equipped and staffed to perform field tests of HEMP protection subsystems and does perform these tests as a normal service. Test equipment shall be of recent and proven calibration and shall provide at least the dynamic range specified for the testing.

80.1.1 Scope. This part addresses the acceptance test requirements for the HEMP protection subsystem including the HEMP shield, protection for all penetrations of the HEMP electromagnetic protection subsystem, and special protective measures.

80.1.2 Requirements. Acceptance testing for the HEMP shield, shielded doors and access covers, WBC protective devices, filter/ESA assemblies, shielded conduits, and special protective measures for the condensing units shall be in accordance with MIL-STD-188-125 and specifications herein.

80.1.3 Qualifications. All testing required under this part shall be performed by an independent testing agency or consultant, experienced in HEMP testing. The testing agency or consultant shall have successfully performed comparable testing on at least five facilities in the last 10 years. The Government reserves the right to approve the testing agency or consultant, based upon credentials provided in accordance with A.80.2.1 and other available information.

80.2 Submittals. The following submittals shall be provided to the Contracting Officer in accordance with A.10.7.

80.2.1 Testing agency credentials. At least 90 days before the start of testing, the contractor shall identify and provide experience information for the agency or consultant that will perform the HEMP protection subsystem acceptance testing. As a minimum, the information shall include the following:

a. Statement of capabilities including the number of employees, years in business, and contract experience.

b. List of at least five installations where comparable shielding effectiveness and pulsed current injection tests have successfully been performed within the last 10 years. Names and telephone numbers of contacts that can verify satisfactory performance shall be provided.

80.2.2 Acceptance test plan and procedures. A detailed test plan and procedure for acceptance testing of the HEMP protection subsystem shall be submitted at least 30 days before the planned date of conduct in accordance with A.10.7.6.1.

80.2.3 Acceptance test report. The acceptance test report for the HEMP protection subsystem shall be submitted within 15 days after completion of the test in accordance with A.10.7.7.1.

80.3 Requirements.

80.3.1 General quality assurance requirements. General quality assurance require ments—including notifications of inspections and tests, Government witnesses, and reme dial actions-shall be in accordance with A.10.6.

80.3.2 Shielding effectiveness test. The HEMP shield and all shielded doors and access covers, WBC protective devices, and filter/ESA assemblies on HEMP electromagnetic barrier penetrations shall be tested for shielding effectiveness in accordance with acceptance test procedures in MIL-STD-188-125, appendix A. The pass/fail criteria shall be in accordance with MIL-STD-188-125 appendix A.

80.3.3 Puked current injection test. All filter/ESA assemblies and shielded conduits protecting electrical penetrations of the HEMP electromagnetic barrier shall be pulsed current injection tested in accordance with MIL-STD-188-125, appendix B. The pass/fail criteria shall be in accordance with MIL-STD-188-125 appendix B.

80.3.4 Condensing units.

80.3.4.1 Shielded conduits and enclosures. The system of shielded conduits and enclosures containing condensing unit wiring and control circuits shall be acceptance tested. The test shall be performed using the pulsed current injection acceptance test procedures for shielded conduits in MIL-STD-188-125, appendix B. Current responses on wiring within the system of shielded conduits and enclosures shall meet the applicable residual internal stress requirements for intrasite power lines and intrasite control/signal lines in MIL-STD-188-125, appendix B.

80.3.4.2 Filter/ESA tests. Filter/ESA assemblies on electrical penetrations of the system of shielded conduits enclosures containing condensing unit wiring and control circuits shall be acceptance tested. The test shall be performed using the pulsed current injection test procedures for intrasite power lines and intrasite control signal lines in MIL-STD-188-125, appendix B. Current responses at the internal terminals of the filter/ESA assemblies shall meet the applicable residual internal stress requirements in MIL-STD-188-125, appendix B.

COST OF HEMP PROTECTION

10. GENERAL

10.1 Scope. This appendix provides supporting cost information for the HEMP hardening of fixed, ground-based C^4I facilities. The data to be presented are taken from unpublished HEMP hardening cost studies by the U.S. Army Corps of Engineers, the Air Force Civil Engineering Support Agency, the Defense Information Systems Agency, and the Defense Nuclear Agency.

10.2 Applications. This cost information is provided for use, as appropriate, in generating HEMP program budget estimates.

20. INITIAL CONSTRUCTION, ACCEPTANCE TESTING, AND HEMP COSTS

The initial construction cost for a HEMP protection subsystem includes all labor and materials for shield assembly, purchase or fabrication and installation of POE protective devices (shielded doors, waveguides-below-cutoff, filters and surge arresters, etc.), and special protective measures provided under the building construction contract. It also covers hardness quality assurance and acceptance testing for these hardening elements. An appropriate fraction of the contractor's overhead, other general expenses, and profit should be allocated to the HEMP hardening cost.

Data from which these costs may be estimated are available from four sources, which are identified in B.10.1. Figure 194 summarizes the total building construction costs for 35 HEMP-hardened facilities as a function of the HEMP-protected floor area. Each of these facilities is a globally shielded, single-story building, so that the total floor area and the HEMP-protected floor area are virtually identical. All costs are stated in Fiscal Year (FY) 1990 dollars. Conversions for raw figures in construction-year dollars were made using producer price indices (industrial) obtained from the Economic Report to the President for Fiscal Year 1989 and Government estimates of producer price inflation for FY 1990. Note that the figures are for the building construction project only, and they do not include costs for the mission equipment or its installation within the facilities.

The facilities are located in the continental United States and Hawaii. Information for 10 of the sites comes from the DNA cost study, and breakdowns of these data will be discussed in significantly greater detail below. The remaining 25 sites are satellite communications facilities, and the cost figures were provided by the Defense Information Systems Agency. No further breakdowns of these costs are available. Although none of the

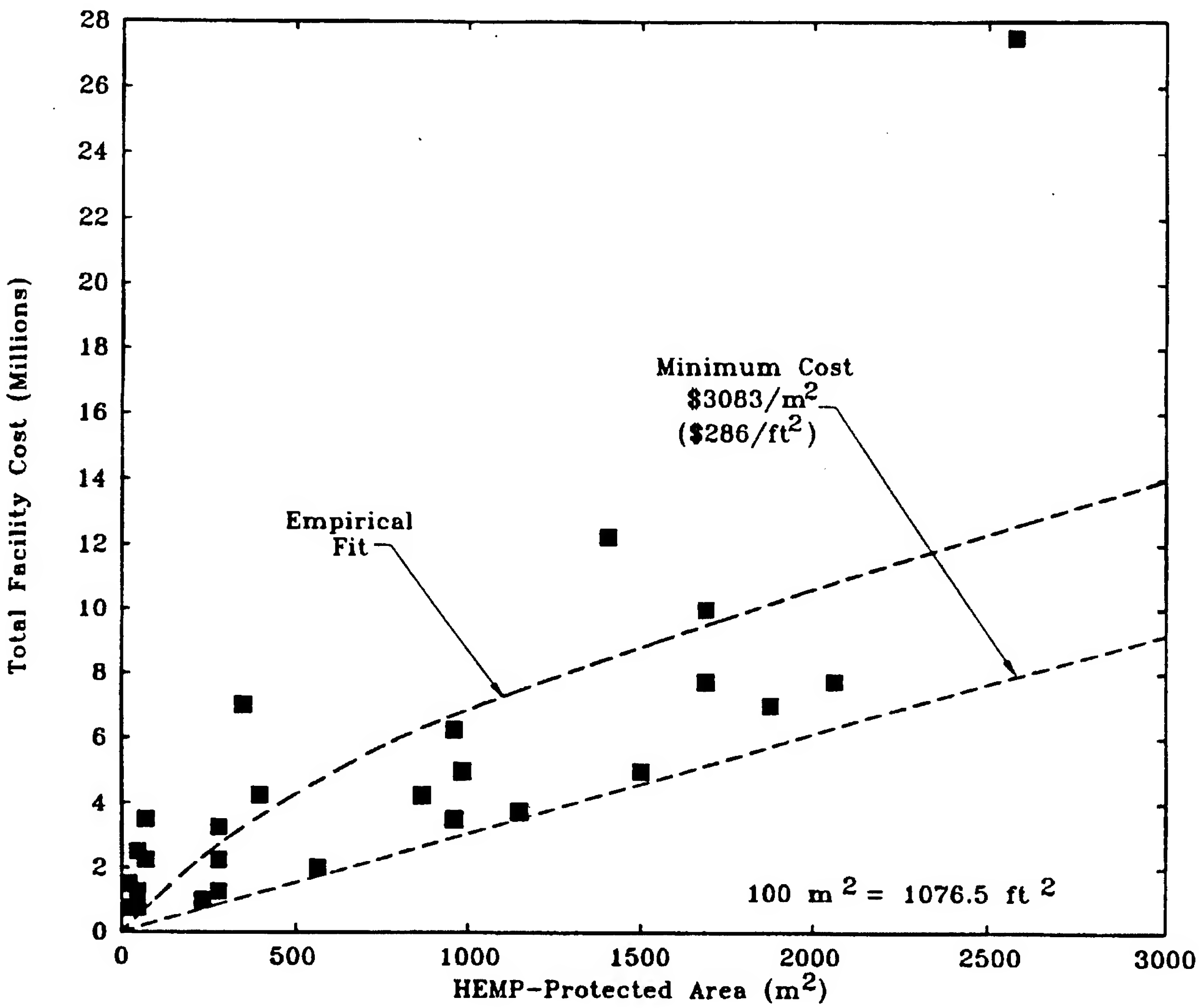


FIGURE 194. Total building construction cost versus HEMP-protected floor area.

facilities were hardened in strict compliance with MIL-STD-188-125 because they predate the standard, the HEMP protection approaches and requirements were very similar to those in the standard.

Figure 194 implies a lower bound on the total building construction cost per unit area of HEMP-protected floor space of $3083/m²($286/ft²). Variations by factors as large as five are found. The studies, however, did not attempt to explain the reasons for such large differences. An empirical fit of the form

$$c_c = aA(1+be^{-A}) \tag{32}$$

where C_c is the total facility cost, A is the HEMP-protected area, and a and b are constants, is also shown.

The data presented in table XXXIV are taken from the DNA study and were originally compiled from USACE, NAVFACENGCOM, and Air Force documents. All cost figures included in the table are based upon at least two sources—usually, the architect-engineer's final design estimates and records of actual costs incurred by the Federal Government. Areas listed as the HEMP-protected floor space were obtained from design planning documents and were verified with dimensions shown in the as-built drawings. The information is considered to represent a verifiable database and, with the possible exception of HEMP-allocated costs, to be accurate within a few percent.

Eight of the sites in the DNA study represent new construction projects, and the remaining two facilities are HEMP-hardened retrofit programs. All projects occurred in the period from 1983 through 1990, and all facilities except the generator building are fixed, ground-based C^4I systems. Sizes range from a minimum of 228 m²(2454 ft²) of HEMP-protected floor area to a maximum of 2593 m²(27,914 ft²).

The mean total building construction cost per unit area (average of the entries in column 4 of table XXXIV) for sites in the DNA sample is $4142/m²($385/ft²). A slightly lower figure is obtained if the sum of building construction costs is divided by the sum of the HEMP-protected floor area entries. Variations from this average are relatively small, with the maximum being about 30 percent. These are significantly less than the differences in the larger sample represented by figure 194.

The mean cost allocated as HEMP protection subsystem cost per unit area (average of entries in column 6) is $1256/m²($117/ft²), which is slightly in excess of 30 percent of the total. The amount of variation in this figure is substantially greater than the differences in total construction cost per unit area, because of two facilities with HEMP costs per unit

TABLE XXXIV. HEMP protection costs for U.S. ground-based facilities.

Facility	HEMP-Protected Floor Area (m^2)	Total Building Construction Cost (FY 1990 $)	Building Construction Cost/Area ($/$m^2$)	HEMP Protection Cost (FY 1990 $)	HEMP Protection Cost/Area ($/$m^2$)	HEMP Protection Cost (% of Total Construction Cost)
Communications Terminal Eastern Continental United States (CONUS)	2,593	7,995,224	3,083	862,181	332	11
Satellite Communications (SATCOM) Terminal Western CONUS	1,682	7,718,212	4,589	1,856,359	1,104	24
SATCOM Terminal Central CONUS	1,122	3,605,601	3,212	1,691,015	1,507	47
ADP Facility Eastern CONUS	966	5,089,469	5,268	1,257,653	1,302	25
SATCOM Terminal Central CONUS	946	3,443,405	3,638	1,004,050	1,061	29
Generator Building Eastern CONUS	875	4,254,411	4,862	423,043	483	10
SATCOM Terminal Eastern CONUS	332	1,451,639	4,374	527,713	1,590	36
ADP Facility Central CONUS	305	1,203,007	3,942	519,363	1,702	43
SATCOM Terminal Western CONUS	299	1,406,475	4,702	591,127	1,976	42
SATCOM Terminal Central CONUS	228	856,034	3,755	342,824	1,504	40

area far below the average. If these two facilities are omitted from the averages, the HEMP protection subsystem cost per unit area is $1468/m^2($136/ft^2) and 33 percent of the total. Again, the cause for these differences has not been investigated.

A second independent estimate of the total building and HEMP protection subsystem construction costs per unit area is provided by the Corps of Engineers study. The USACE sample consisted of six facilities in the continental United States and overseas, and the analysis approach was very similar to that of the DNA effort. Principal results from this study are as follows:

- Mean total building construction cost (in FY 1990 dollars) – $3007/m^2($279/ft^2)
- Mean HEMP construction cost (in FY 1990 dollars) – $1353/m^2($126/ft^2), which is 45 percent of the total

Furthermore, construction costs for HEMP-hardened facilities have also been estimated with the SATCOM Shelter Cost Model, which was developed by the Construction Cost Management Group, Air Force Civil Engineering Support Agency, Tyndall AFB, Florida. Table XXXV provides a comparison of results from the empirical DNA and USACE studies with calculations from the model. The agreement is sufficiently good to justify the use of an average of these figures for budgetary construction cost estimates.

The discussion to date has focused upon predicting HEMP hardening costs from a single parameter—the HEMP-protected floor area. This simplistic algorithm, however, should be used cautiously when accurate figures are required. In fact, these costs will be determined by a variety of parameters describing the HEMP hardening features. Significant construction savings can be realized by carefully minimizing the number of barrier penetrations and eliminating requirements for special protective measures, wherever possible. More complex and accurate models to estimate the HEMP hardening costs based upon site-specific design factors are under development. These factors are expected to include the number of shielded doors, numbers and types of mechanical and electrical POEs, and information regarding special protective requirements, as well as shield area.

30. HEMP COST DURING COMMUNICATIONS-ELECTRONICS EQUIPMENT INSTALLATION

HEMP hardening tasks during installation of the communications-electronics equipment are generally very limited in scope. A small number of POE protective devices will usually be provided for system-unique penetrations, such as rf waveguides or antenna and antenna control lines, which were not fully defined to the building architect-engineer.

TABLE XXXV. Comparison of HEMP protection costs from independent sources.

Source	Mean HEMP Protection Cost ($/m^2)	Standard Deviation HEMP Protection cost ($/m^2)	Mean HEMP Protection Cost (% of Total Construction Cost)
DNA Study	1256	526	30
USACE Study	1353	161 (estimated)	45
SATCOM Cost Model	1514	NOT AVAILABLE	38

Some special protective measures may be required for MEE that must be placed outside the electromagnetic barrier. These tasks also include hardness quality assurance and acceptance testing of HCIs installed during this phase.

The costs for HEMP tasks during the C-E equipment installation phase are likely to be very system- and site-specific. To date, there have been no attempts to establish a database of these costs.

40. HEMP VERIFICATION COST

Hardness verification testing represents a one-time cost, to be incurred after completion of the construction project and C-E equipment installation. The handbook also recommends periodic hardness surveillance/revenfication tests, but these will be treated as HM/HS costs (see B.60).

Based upon past experience at 12 facilities tested using methods similar to the procedures specified in MIL-STD-188-125, the typical cost in FY 1990 dollars for a verification program will range from $250,000 to $700,000 (or approximately $75,000 per test week). The price covers pretest planning, test performance, and documentation of the measured results, and it includes labor, travel, and miscellaneous expenses for expendable supplies and site-unique experimental fixtures. The price does not include acquisition and maintenance of HEMP simulators and instrumentation, which were Government-furnished at no cost in the cited test programs. It also does not cover costs of facility modifications to correct the observed HEMP hardness deficiencies.

In these past programs, the verification cost has tended to be greater for a larger facility. Some reduction of costs (in FY 1990 dollars) can reasonably be projected as more tests are performed and greater familiarity with the MIL-STD-188-125 procedures is acquired.

50. HM/HS PLAN DEVELOPMENT COST

HEMP hardness maintenance and surveillance plans have been written for numerous fixed, ground-based C^3I facilities by a variety of DoD agencies and contractors. These documents have varied greatly in the nature and the depth of their content. As a result, there is also wide disparity in their preparation costs—ranging from a few thousand dollars to several hundred thousand dollars. The information based on past experience is not particularly useful for estimating the cost of developing an HM/HS plan with the program elements recommended in this handbook.

60. HARDNESS MAINTENANCE AND SURVEILLANCE COSTS

Hardness maintenance and hardness surveillance represent continuing costs over the life of a HEMP-protected facility. The costs are incurred for labor and supplies to perform routine hardness preventive maintenance and inspections, for labor and parts to repair or replace defective HCIs, for periodic hardness surveillance/reverification testing, and for training.

Annual routine HEMP hardness preventive maintenance and inspection costs are relatively low. At two facilities where these tasks are performed by contractors, the contract prices in FY 1990 dollars are less than $10,000 per year. Costs for the somewhat more aggressive program recommended in the handbook should be within a factor of two times the $10,000 figure.

Hardness surveillance/reverification test costs will vary with the frequency and completeness of the testing. If complete reverification is required, the cost per test can be estimated from the data previously presented in B.40. If measurements will be performed on a one-third sample of HCIs and on hardening elements repaired, modified, or added subsequent to the previous test, for example, the cost per surveillance/reverification test might be approximately 50 percent of that for a full verification program. The 50 percent figure also appears to be reasonable for the surveillance testing program recommended in this handbook.

There are no validated data for annual HEMP repair costs or HEMP training costs,

DATA ITEM DESCRIPTIONS

10. INTRODUCTION

This appendix lists data item descriptions (DIDs) which may be used in preparing various documents required during a HEMP hardening program. The tabulation is limited to the data item descriptions that are discussed in the main body of MIL-HDBK-423. A much more extensive compilation is found in the Defense Nuclear Agency report 'Military Handbook for Hardness Assurance, Maintenance, and Surveillance (HAMS) Planning" (reference C–1). This reference also identifies data item descriptions in related disciplines, such as system engineering and logistics support analysis, that are not specifically oriented to HEMP or nuclear survivability.

New data item descriptions are produced frequently, and older ones are cancelled or superseded. Reference C–2 provides a current tabulation of the data item descriptions that may be applied in Department of Defense contracts. Lists are organized numerically, by functional or standardization area, and by key words. Cancelled and superseded data item descriptions are also listed and, in the latter case, the superseding data item description is identified.

20. DATA ITEM DESCRIPTION LISTS

20.1 Facility (nuclear survivability and HEMP) requirements. The facility requirements document formally establishes the functional requirements that a design and construction project must satisfy in order to meet the needs of the user. As discussed in section 21 of this handbook, a section of the document addresses survivability when HEMP or other survivability specifications are to be levied. The following data item descriptions identify the nature and depth of the information to be provided in the facility requirements document:

DI-E-1136	– Site Facilities Design Data.
DI-S-3557	– Facility Design Criteria.
DI-FACR-81045	- Facilities Requirements Document for Typical Shorebased and Shipboard Sites.

20.2 Nuclear survivability and HEMP program plan. The HEMP program plan is a management tool, used for coordination of the numerous tasks that constitute a complete HEMP hardening program. The information that should be included in the plan is discussed in handbook section 21 and the following data item descriptions:

DI-NUOR-80156A - Nuclear Survivability Program Plan.
DI-ENVR-80262 - Nuclear Hardness and Survivability Program Plan.

20.3 Nuclear survivability and HEMP design report. The following data item descriptions outline the content of a HEMP design analysis and trade study report:

DI-ENVR-80266 - Nuclear Hardness and Survivability Design Analysis Report.
DI-ENVR-80267 - Nuclear Hardness and Survivability Trade Study Report.
DI-NUOR-80927 - Nuclear Survivability Design Parameters Report.

In the development of a HEMP-hardened, ground-based facility, such reports are typically required to document performance predictions for electrical POE protective devices (see section 12) and special protective designs (see section 14).

20.4 Nuclear survivability and HEMP test plan and procedures. HEMP acceptance, verification, and surveillance/reverification test plans and procedures should be prepared in accordance with MIL-STD-188-125 and the following data item description:

DI-NUOR-80928 - Nuclear Survivability Test Plan.

The requirements for these test sequences are described in handbook section 16. Based on these requirements and the information specified in the above DID, outlines for the test plans are developed and presented in section 21.

20.5 Nuclear survivability and HEMP test report. Outlines for HEMP acceptance and verification test reports are provided in section 21. The test report for the hardness surveillance/reverification program should contain the same information as the verification test documentation. These outlines were developed from the requirements of MIL-STD-188-125 and the following data item description:

DI-NUOR-80929 - Nuclear Survivability Test Report.

20.6 Nuclear survivability and HEMP hardness maintenance and hardness surveillance plan. Guidance for the preparation of the HEMP hardness maintenance and surveillance plan is found in the following data item descriptions:

DI-ENVR-80264 - Hardness Maintenance Plan.
DI-ENVR-80265 - Hardness Surveillance Plan.
DI-NUOR-81025 - Nuclear Survivability Maintenance/Surveillance Plan.

Handbook section 20 defines the elements that are included in the HM/HS program. As previously described for test plans and reports, a suggested outline for the HM/HS plan is presented in section 21.

20.7 Configuration management plan. Data item descriptions that may be used in the preparation of the hardness configuration management plan (see section 19) are listed below:

DI-E-3108 - Configuration Management Plan (CMP).
DI-CMAN-80858A - Configuration Management Plan.

While these DIDs do not explicitly address HEMP, the information requirements are applicable to all types of managed configuration items including a HEMP protection subsystem.

20.8 Reliability, maintainability, and testability program plans. Section 17 recommends that formal reliability, maintainability, and testability programs be established during the design phase for a MIL-STD-188-125 HEMP-hardened facility. Development of program plans for these efforts (or a single plan for the combined activities) is one of the suggested tasks. The following DIDs should be used in preparing the plan or plans:

DI-R-7079 – Reliability Program Plan.
DI-T-7198 - Testability Program Plan.
DI-MNTY-80822 – Maintainability Program Plan.

30. REFERENCES

C-1. Thompson, C., and R. Beaty, "Military Handbook for Hardness Assurance, Maintenance, and Surveillance (HAMS) Planning" DNA-TR-89-281, Defense Nuclear Agency, Alexandria, VA, September 1990.

C-2. "AMSDL - Acquisition Management System and Data Requirements Control List," DoD 5010.12 (effective), Dept. of Defense, Washington, DC.

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CONCLUDING MATERIAL

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- Air Force-90

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(Project SLHC 4230)

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- Army-AC,AM,ET,PT
- Navy-MC,NC,OM,TD
- Air Force-01,02,13,14,15,17,19,21,93
- DLA—DH
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- Navy-YD
- Air Force-50,80

Civil Agencies Coordinating Activities:
- TRANSPORTATION—OST

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

INSTRUCTIONS

1. The preparing activity must complete blocks 1, 2, 3, and 8. In block 1, both the document number and revision letter should be given.
2. The submitter of this form must complete blocks 4, 5, 6, and 7.
3. The preparing activity must provide a reply within 30 days from receipt of the form.

NOTE: This form may not be used to request copies of documents, nor to request waivers, or clarification of requirements on current contracts. Comments submitted on this form do not constitute or imply authorization to waive any portion of the referenced document(s) or to amend contractual requirements.

I RECOMMEND A CHANGE:	1. DOCUMENT NUMBER MIL-HDBK-423	2. DOCUMENT DATE (YYMMDD) 930515

3. DOCUMENT TITLE High-Altitude Electromagnetic Pulse (HEMP) Protection for Fixed and Transportable Ground-Based C4I Facilities; Vol I, Fixed Facilities

4. NATURE OF CHANGE *(Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)*

5. REASON FOR RECOMMENDATION

6. SUBMITTER

a. NAME *(Last, First, Middle Initial)*	b. ORGANIZATION	
c. ADDRESS *(Include Zip Code)*	d. TELEPHONE *(Include Area Code)* (1) Commercial (2) AUTOVON *(If applicable)*	7. DATE SUBMITTED (YYMMDD)

8. PREPARING ACTIVITY

a. NAME	b. TELEPHONE *(Include Area Code)*	
AFC4A/TNAB	(1) Commercial (618) 256-2975	(2) AUTOVON 576-2975
c. ADDRESS *(Include Zip Code)* 607 Pierce Street, Room 300 Scott AFB, IL 62225-5421	IF YOU DO NOT RECEIVE A REPLY WITHIN 45 DAYS, CONTACT: Defense Quality and Standardization Office 5203 Leesburg Pike, Suite 1403, Falls Church, VA 22041-3466 Telephone (703) 756-2340 AUTOVON 289-2340	

NOTICE OF VALIDATION

INCH-POUND

MIL-HDBK-235/1B
NOTICE 1
22 December 2000

MILITARY HANDBOOK

ELECTROMAGNETIC (RADIATED) ENVIRONMENT CONSIDERATIONS FOR DESIGN AND PROCUREMENT OF ELECTRICAL AND ELECTRONIC EQUIPMENT, SUBSYSTEMS AND SYSTEMS

MIL-HDBK-235/1B, dated 1 May 1993, has been reviewed and determined to be valid for use in acquistion.

Custodians:
Army - CR
Navy - EC
Air Force - 11
Other - DC5

Review Activities:
Army - AR, AV, MI, TE
Navy - AS, MC, SH
Air Force - 18, 19

Preparing activity:
Other - DC5

AMSC N/A **AREA EMCS**

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